

A MODEL OF ERROR PROPAGATION  
FROM DIGITAL ELEVATION MODELS TO VIEWSHEDS

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The purpose of this research is to develop a model of error propagation from digital elevation models (DEMs) to viewsheds. The hypothesis that guides the research is that the error in the viewsheds is a function of the error in the DEM, the terrain conditions, and the height of the observation point. Further, it is hypothesized that the error in the DEM is dependent, in part, on the method of production used to create the DEM. This is tested by comparing several test DEMs for the same study area with a control model that serves to represent truth.

The use of the control DEM makes it possible to determine both the magnitude and the pattern of the error in the test DEMs. Further, it is used to create viewsheds, or areas of visibility, that are compared with the viewsheds created with the test DEMs. A comparison of the differing ability of the test DEMs to produce accurate viewsheds is the

major emphasis of this research. It is found that the contour-interpolated viewshed has the lowest magnitude of error. The DEM created from high altitude aerial photography using an automated correlation technique performs next best. The DEM from the United States Geological Survey is the third, and the DEM derived from SPOT (Systeme Pour l'Observation de la Terre) imagery is fourth most accurate.

It is also found that errors of omission and errors of commission in the viewsheds are significantly different for the different DEMs. Path diagrams illustrate the proposed models of error propagation from the DEMs to viewsheds. The error models account for the sources of DEM error, the degree to which these contribute to errors of omission and commission in the viewsheds, and the manner in which the type of viewshed error affects the validity of the viewsheds.

## CHAPTER I INTRODUCTION

### Background

A digital elevation model (DEM) is a digital representation of the shape of the earth's surface. The DEM in a geographic information system (GIS) plays the role contour lines and shaded relief renderings play on traditional paper maps. All DEMs contain error, but the magnitude and spatial distribution of the error vary. This research focuses on error in several gridded DEMs when the DEMs are produced by different methods. The analysis investigates the causes of the error and the consequences of the error when the DEM is used in a GIS to estimate a viewshed.

The test DEMs evaluated here were

- 1) A DEM derived from 10 meter digital SPOT imagery
- 2) An experimental high density DEM from high altitude aerial photography
- 3) Five United States Geological Survey 30 meter DEMs
- 4) A contour interpolated DEM produced with GIS software.

A reference model served as the basis for "truth." Accuracy is defined as conformance to true values, so the reference model provided a proxy for true values. The reference model, itself, was considered of higher accuracy than the test models, due to the scale of

its source data and manner in which it was produced. The reference was produced with 1:24,000 scale air photos and traditional photogrammetric methods.

From the time that digital elevation models were first introduced in the late 1950s until the present, tremendous changes have occurred in digital mapping. Geographic Information Systems (GIS) have become a focal point for many of the developments of techniques to display, store, transform and analyze digital spatial data. A DEM is a key component of many GISs intended for natural resource management. In many cases, the DEM provides the backbone for the analysis. Without a valid DEM, the output of many a GIS analysis may be put in the garbage heap with the other "garbage in" that becomes "garbage out."

A DEM within a GIS capable of full utilization of the DEM represents a powerful tool. The technology required to create this tool has been a fairly recent achievement, and its full potential has not been exploited. This combination has been realized only after a multitude of small contributions from a number of disciplines -- notably, photogrammetry, remote sensing, geography, and computer science. As these inter-related disciplines have worked on the problem of DEM production, they have, also, increasingly, become aware of the DEM accuracy problem. Because of the enormous potential for data misuse that a GIS allows, the context of a GIS is particularly challenging.

### Problem Statement

A variety of DEMs from different sources and using different production methods are available to the GIS analyst. Intermediate-scale mapping at a scale of about 1:24,000

to 1:100,000 is often appropriate for natural resource based GIS projects. Even if the DEM market is confined to intermediate-scale mapping the number of methods to produce a DEM can be difficult to understand. This is especially true when the GIS user lacks a background in the mapping sciences. How can the GIS analyst make an informed decision about the best DEM for their application? In particular, how can the GIS analyst discuss the problem with a data vendor or producer in an intelligent manner in order to learn the information they will need to make that judgement? These questions were the impetus for this research.

It is difficult for the user of a DEM to assess the nature of the problem of error (Bolstad and Smith, 1992). This is true, in part, because information about the error in DEMs has not been documented in a way that is useful to the user. The error calculation most commonly reported, the root mean square error (RMSE), tells something about the average error, but reveals nothing about the location and absolute magnitude of the error. Also, the RMSE varies with the location and number of check points used in its calculations (Li, 1991). The error in rugged terrain and forested areas is almost always greater than in other areas, so if check point locations do not represent those areas in proportion to their occurrence, the RMS error will not be representative of the model (Torlegard, Ostman, and Lindgren, 1984).

A further problem is simply a lack of information about the error. As Openshaw (1989) noted, surprisingly little information about error in GIS databases is available to the GIS analyst, and the tendency is to ignore the problem. Fisher (1992: 1322) wrote about DEMs that "[h]ow the error is distributed across the area of any one [DEM] is

currently unknown, and factors that may affect the distribution of error are largely unresearched." The spatial pattern of the error will be most apparent when the entire test surface is compared to a control of higher accuracy. This approach was followed in this research.

A better understanding of the nature of the error in DEMs will provide the user of a DEM information about the potential error in their analyses involving the DEM. Error in elevation models has a significant effect on the validity of models derived from the DEMs (Lee, Snyder and Fisher, 1992; Fisher, 1992; Walsh, Lightfoot and Butler, 1987). Many GIS analyses rely on estimates of elevation. They are useful to delineate watersheds and to determine flood plains. In addition, they are a key component in soils mapping, in vegetation studies, and in many facilities location analyses. How does the error in the DEM affect the outcome of such analyses?

This research focused on the DEM-intensive application of viewshed calculation. Viewsheds, or visibility regions, have been useful to military planners and landscape architects, in particular, but also have a broader usefulness and are a common tool in the GIS toolbox. The accuracy of the DEM is a key component in the validity of the viewshed calculation.

### Research Objectives

This research had two major objectives:

- 1) Assess the location and magnitude of error in DEM test models created by common production methods compared to a high accuracy control DEM.

- 2) Determine the relationship between the error in the test models and the error in viewsheds calculated from those models, and develop a conceptual model to summarize that relationship.

In all cases, the test models were compared to a higher accuracy control model.

In mapping, money buys truth. All else being equal, the more money, the more truth. The cost of the control model was considerable, and the level of "truth" was correspondingly high. The relative amount of truth available in the test models was revealed through the accuracy assessment. The degree to which the lack of truth affects the validity of the GIS viewshed operation was the final product of this investigation.

### Presentation of the Research

Following this introductory chapter, Chapters II, III, and IV provide an overview of the literature related to the accuracy of DEMs. The terms and definitions used in this literature have not been consistent, and Chapter II is devoted to tracing the source of the usage of several terms over the past thirty years. In addition, it establishes the definitions and concepts applicable to this research.

Chapter III looks specifically at DEM production methods, with a focus on those represented among the test DEMs for this study. In addition, it examines the relationship between photogrammetry and GIS, and the role of photogrammetry within the GIS industry today. Chapter IV then discusses accuracy issues related to the DEMs described

in Chapter III. Chapter IV also provides an overview of results of past empirical studies related to DEM error from various methods.

Chapters V, VI, and VII report on the results of the empirical research which is the main object of this dissertation. Chapter V describes the data set used for the tests. Chapter VI is an overview of the error in the test models. This corresponds to the first research objective given above. The results of the second research objective are found in Chapter VII, where the propagation of error in the test models is analyzed in view of its role in the viewshed calculations. The model of error propagation is presented at the end of Chapter VII. Chapter VIII is a summary and conclusion of this work, and it provides suggestions for future research in this area.

## CHAPTER II DIGITAL ELEVATION MODELS

### Concepts, Terms and Definitions

#### DEM or DTM?

A digital elevation model (DEM) is a digital representation of the earth's relief for a specified geographic region. The term "digital terrain model," or DTM, has been used interchangeably with DEM, and common usage of the terms is not consistent. DTM was the earlier term. It first appeared in the late 1950s, when transportation planners at the Massachusetts Institute of Technology defined it as:

a statistical representation of the continuous surface of the ground by a large number of selected points with known xyz coordinates in an arbitrary coordinate field (Miller and Laflamme, 1958:435).

DEM often describes the same concept as given above for DTM, though DTM is more common than DEM. Other terms have been used for similar models including "digital height model," "digital ground model," "digital surface model" and "digital terrain elevation data" (DTED). The usage tends to reflect the national origin or place of education of the person using the term (Li, 1990). For example Ackermann (1980), from Germany, wrote about digital height models, and in Britain, it is common to use the term digital ground model (Li, 1990).

Both DEM and DTM are common terms used in the United States. Exact definitions of these two terms have not been clearly established. Carter (1988), chose a his/her approach, calling the models DTM/DEM. This is cumbersome, and it sidesteps the possibility of a meaningful distinction between the two terms. A useful distinction may be found by an examination of two general meanings of the older term, DTM. These two meanings provide a way to relate DEMs with DTMs and to define the way elevation models fit within the context of GIS data bases today.

In 1976, Makarovic described two views of DTMs; one broad and one narrow. In the narrow, sense, he wrote, "a DTM represents terrain relief data, but with distinct morphological data included" (1976:57). In the broad sense, "a DTM includes both planimetric detail, and terrain relief data, in digital form." In addition, he suggested that a "DTM system" would be capable of handling a DTM at all production stages. These three concepts continue to have merit, and their use in the context of this thesis follows.

### The Term "DEM"

The term DEM will be used to express the narrow view of DTM. This means that the use of DEM will be consistent with the definition by Miller and Laflamme (above) for DTM. Helava, in a discussion in 1978, went so far as to reject the broader view, stating that though he agreed that "there is a great attraction to a wider definition [of DTMs, t]he origin of our concept was dealing simply with terrain elevations expressed against their position" (Mikhail *et al.*, 1978:1488). He argued that when the database

included other information than elevation, the system should have some name other than DTM.

Burrough expressed his view on the matter, stating that because the word "terrain" implies other aspects of the landscape beyond elevation, "the term DEM is preferred for models containing only elevation data" (Burrough, 1987:39). Makarovic' stipulation that distinct morphological data be included will not be followed strictly. The section in this chapter on data structures addresses this issue in more detail.

### The Term "DTM"

Burrough did not elaborate on what constituted a terrain model. Help with this issue comes from Collins and Moon (1981), who considered a DEM to be a sub-unit of a DTM. They stated that a "Digital Terrain Model is an array of numbers that represents the spatial distribution of a set of properties of the terrain" (1981:71). The DEM contained only information on elevation and the DTM included a DEM, as well as other information, such as soil type, land use, or hydrographic features.

When the term DTM is used in this research, it will refer to the more inclusive view just described. This view reflected the understanding that it was in combining elevation with other map information that its analytical potential could be realized. Most of the work presented here deals only with DEMs, so the exact properties that constitute a true terrain model are left for others to consider.

### DTM Systems and Geographic Information Systems

Data alone do not solve problems. They must be in a useful context. In 1976, Makarovic described a DTM system that focused on the production of DTM. It would be capable of handling all aspects of DTM creation, but would not necessarily be used for analysis. This fits in well with the photogrammetric tradition of which he was a part. Frederiksen, Jacobi and Kubik, from the same tradition, elaborated on this idea, and defined a DTM [system] as "a program package consisting of routines for data storage, data retrieval, editing, interpolation and contouring" (1985:101). Analysis was still omitted.

More recently, Weibel and Heller (1990b) described a DTM system that would include the ability to generate, manipulate, interpret, visualize, and apply a DEM. Their system included the analysis aspect of DEMs. The use of "DEM" in this case reflects the usage established for this research. The analogous concept used by Weibel and Heller was a "structured model," which was a second generation product produced by manipulating the original elevation values measured from images into the particular format required by analysis software.

The analysis software of Weibel and Heller is very similar to a geographic information system (GIS). Geographic information systems are computer software and hardware for acquisition, preprocessing, management, manipulation and analysis, and output of spatial data (Star and Estes, 1990). Other important components of a GIS are the personnel who develop and use it, the institutional setting and the geographic data base, itself. The functions of a GIS are similar to Weibel and Heller's DTM system

functions. For this research, a DTM system is considered as a special type of GIS, which is especially designed for handling elevation data. All GISs do not have, and should not be expected to have, the ability to generate DEMs, nor will all GIS data bases include all aspects of a DTM. However, the GIS that is expected to perform analyses, in which the DEM plays a critical role, should be a DTM system.

Scientific applications of DEMs have roots in SYMAP, short for the Synagraphic Mapping System, conceived and developed by Howard Fisher, while on the faculty at Northwestern University in 1963. Fisher later moved to the Harvard University Laboratory for Computer Graphics and Spatial Analysis, the Lab to which SYMAP is usually attributed. One of Fisher's principal goals with SYMAP, was to allow the cartographic analyst to create a regular grid of Z-values from irregularly spaced points (Sheehan, 1979). This was an important precedent that led to the current use of DEMs in GIS analysis.

### DEMs and Data Structures

The definition of DEM as the digital representation of elevation expressed against its geographic location includes many distinctly different data structures. A data structure defines the way in which the elevation values are stored in the data base. Digital contour lines, irregular triangulations, regular grids, and various mathematically derived models all could serve the purpose of representing the earth's surface elevation (Burrough, 1987; Mark, 1978). Figure 2-1 illustrates these four data structures.

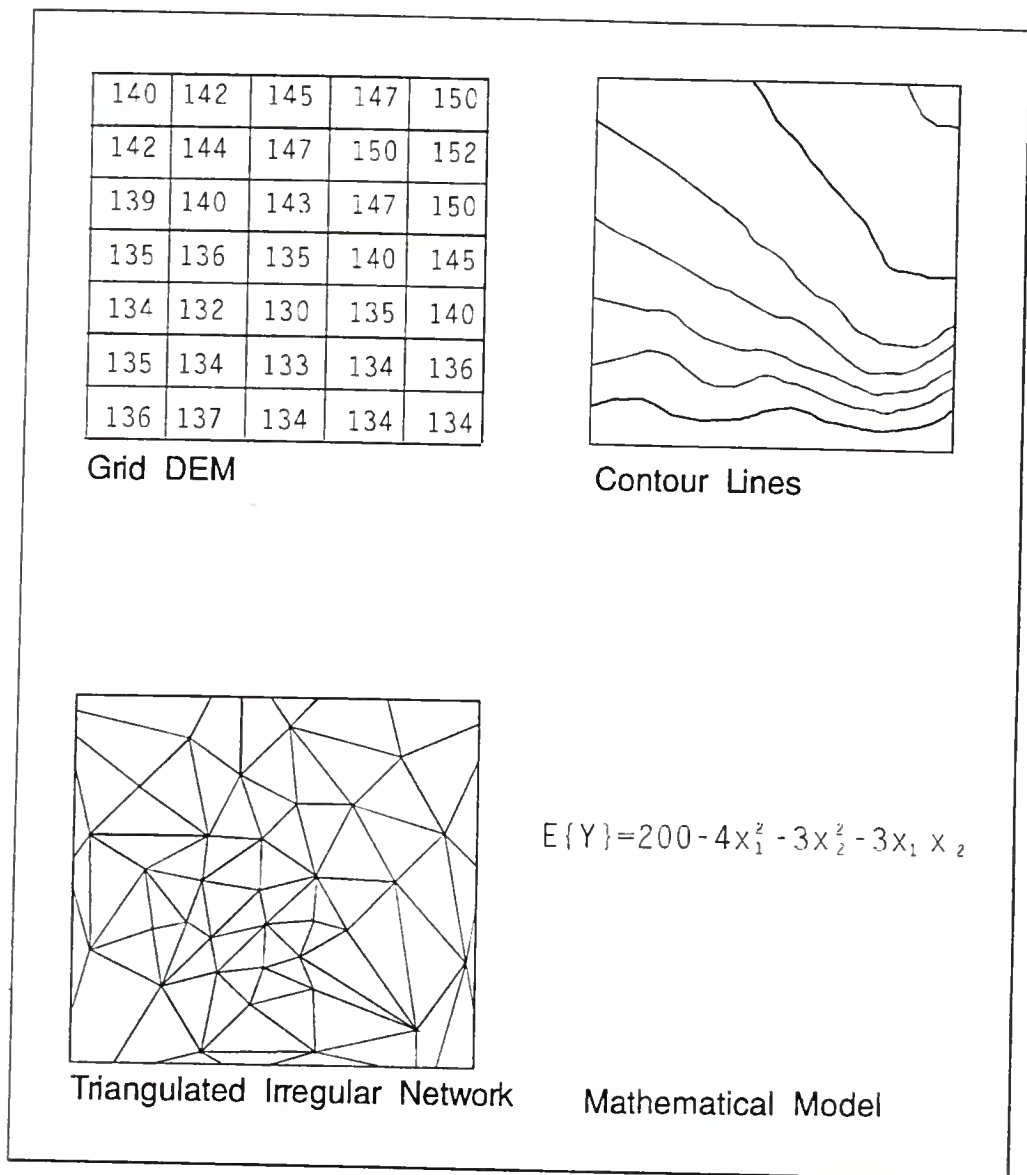


Figure 2-1  
DEM Data Structures

All data structures are not equally amenable to use as an analytical model of elevation in a GIS analysis. For GIS applications, the data structures that have been used the most frequently are the regular grid models and the models created with irregular triangulations (Burrough, 1987). Digital contour lines and mathematical models have been used less frequently in GIS analysis for several reasons discussed below. The grid DEM is the most common form of DEM.

### Grid DEMs

In this research, grid DEMs produced by different methods are the only DEMs under consideration. For this reason, when the term DEM is used without qualification, a grid DEM is implied. Grid DEMs are organized in rows and columns of height values. Each equally-spaced value--also called a z-value--represents a square portion of the earth's surface. Each of these squares is called a grid cell. The z-value associated with a cell is the estimated height of the cell. This is measured as either the average value for the cell or the height estimated for the point at the center of the cell. The horizontal resolution of a grid DEM refers to the length of the sides of each square grid cell. This type of data structure is often called raster data (Burrough, 1987, provides a good discussion).

The format of a grid DEM does not require that explicit information concerning the relationships among the various cells be stored with the z-values. Those relationships are implied by the location of the cells within the matrix. This simple data structure is relatively easy to use in computer programs, adding much to its popularity among programmers. Generally, spatial analysis and digital map overlays with digital data are

simpler with raster data (Burrough, 1987). In addition, grid data are appropriate for terrain visualization (Weibel & Heller, 1990a). The most serious shortcoming of grid DEMs is their inability to store critical features explicitly, such as ridges and breaklines. A brief discussion of the competing data structures follows.

### Digital contour lines

Contour lines are the traditional mainstay of topographic mapping. They are well-understood by map users, and they are used extensively for topographic interpretation. Digital contour lines are frequently included in a GIS land base and remain useful graphically. However, they are cumbersome for computer processing in GIS analysis, and usually, they are not used as input for a quantitative GIS analysis. A major use of contour lines in GIS data bases is as a data source from which gridded DEMs and TINs are created.

### Mathematical models

Surface elevation has been represented by local methods, including piecewise approximations and by global methods, such as Fourier series and multiquadratic polynomials (Burrough, 1987). The smooth, highly abstract nature of mathematical models is more appropriate for depicting surfaces abstractly than for depicting elevation at a particular place. In the opinion of Yoeli, for example "[t]he earth's surface, being completely irregular, is prima facie, devoid of mathematical characteristics (Yoeli, 1984:141). Although mathematical models are used successfully to simulate hypothetical terrain types and are used in computer-aided design systems for modelling complex surfaces (Burrough, 1987), they have been less useful as method to store an easily

accessible DEM in a GIS. Mathematical functions tend to be visually unrealistic when portrayed graphically, because they are often "endowed with peculiarities which are unlikely to appear in reality" (Wolf, 1991:202).

### TINs

After grid DEMs, the second most common DEMs are the triangulated models. The triangulated models are frequently called triangulated irregular networks, or TINs (Peucker et al., 1978). TINs were developed as an alternative data structure to DEMs, and they have several advantages over gridded models. TINs store values more efficiently than grid DEMs, because the density of points in the TIN varies with the roughness of the terrain. With a grid, if the horizontal grid spacing is based on the roughest areas, there will be many redundant points in smooth areas. Another advantage of TINs is that critical points, such as peaks, pits, passes and breaklines, may be stored at their exact location.

A disadvantage of TINs is their complexity. The topology, or definitions of the spatial relationships among the TIN data objects, requires complex computing and considerable computer memory. Further, the algorithms for TINs tend to be much more complicated, for both the programmer and user, than those that deal with grids. In addition, the advantage of accuracy of TINs over grid DEMs, which has long been assumed, was challenged recently in work by Kumler (1992).

Kumler tested the accuracy of two gridded DEMs and six TINs for 25 different study areas, representing a variety of terrain types. He used two different interpolants to create the two gridded DEMs from the same set of digital contour lines. For the TINs,

he used three different methods to select points from digitized contours and three other methods that involved a selection of a subsets of a grid. In selecting the points, the TINs were constrained to be about the same size (in terms of computer memory) as the gridded models. These eight models were produced for 25 different study areas, representing a variety of terrain types. The error in the competing models was tested using three different sets of test points and several error statistics. To his surprise, the TINs did not perform better in terms of accuracy than the grid DEMs that he tested. The accuracy of the grid DEMs was generally of about the same or better accuracy than the TINs.

#### Some Final Thoughts on DEM Concepts

To complete this section on the definition of digital elevation models, several minor issues are addressed. Two terms used in the United States to describe elevation models have taken on special meaning. Digital Terrain Elevation Data (DTED) and DEM are both trade names of a sort. DTED is the name of the elevation model developed and distributed by the United States Defense Mapping Agency (DMA, 1986). DEM is the term used by the United States Geological Survey for the models that comprise the major part of a national digital elevation data base (USGS, 1990). USGS DEMs have been so widely used in the United States that they have become a standard against which other DEM products are compared. DEMs distributed by the USGS will be called USGS DEMs.

Goodchild has noted the difference between a model and a data structure. In a model, he says, every point on the surface is known, as opposed to only discrete elevation

values. The elevation values and their geographic relationships are only data structures, not models (Goodchild, 1992). For the purpose of this research it is assumed that the DEMs are a part of a geographic information system. Thus, though the models, themselves, only include information on elevation, GIS interpolation algorithms make it possible to estimate an elevation value at any point on the surface using the values stored explicitly in the DEMs. The GIS can also be used to derive information on slope, direction of slope (aspect), and visibility regions from the DEM. A DEM, in this context should be considered a true model.

As a final point, the data storage methods and the GIS programs applied to DEMs could also be applied to other surfaces. These could include abstract surfaces portraying land values, pollution, ore distributions or population densities. Though extensions could be made from this research to these other types of surfaces, the elevation of the earth is distinctly different from these other surfaces (Carter, 1988). The surface of the earth is not an abstraction, it is truly continuous and it is a surface about which information can be measured for virtually any location. These factors along with the legacy of photogrammetry and the key role that DEMs play in many GIS analyses makes the focus on DEMs justifiably different from the other surfaces.

### Applications of DEMs

In 1978, Helava commented that practical applications of DEMs had not kept up with theoretical progress. The large volume of data required for DEMs and inefficient

digital storage methods led to high costs and hampered usability. This limitation has been greatly attenuated as advances in both hardware and software have made it possible to realize many practical applications of DEMs. In particular, DEMs have become more widely used with the increasing use of geographic information systems and other technology that facilitates modelling of the natural environment.

Many early DEMs were data without a mission. Some of the earliest DEMs were by-products of the production of orthophotographs (Allder, 1983). An orthophotograph is a vertical photograph from which all distortion, including that introduced by changes in relief across the extent of the photograph, has been removed. In order to remove relief distortion, elevation needs to be measured. As digital methods of orthophoto production became common, the digital elevation values required for the orthophoto were saved (Case, 1981; Hoffman *et al.*, 1982). These elevation values were among the first commonly available DEMs. The availability of DEMs gave rise to applications. Only as applications have become more firmly established and users of DEMs become more aware of the potential problems with DEMs has DEM production become more structured and focused on particular outcomes. Most applications have been related to engineering, scientific investigations, and military operations.

Transportation planners at the Massachusetts Institute of Technology were among the first to explore the functionality of DEMs (Miller and Laflamme, 1958). The traditional, nondigital methods to store elevation data, such as topographic maps, terrain profiles and physical terrain models were useful for human interpretation, they argued; but a DEM, in digital form, was superior for doing numerical interpretation with the digital

computer. A more recent example of the centrality of DEMs in transportation planning is found in Christenson (1988).

The military has also used DEMs (Weibel and Heller, 1990b). Topographic mapping as an aid to strategic planning has been improved by using digital techniques. Visibility regions determined with the DEM have been of particular interest to military planners. Another important use of DEMs has been to guide missiles for long distances. With a DEM on board, the missile can find its path by repeatedly checking for changes in elevation below, and comparing the changes with what is known about the elevation at that point as recorded in the DEM.

One group of scientific applications of DEMs has centered on the areas of geomorphology and hydrology. Examples include Mark (1984), Hutchinson (1989), and Jenson and Domingue (1988). In these applications, the effects of errors in the elevation models are particularly apparent. Mark focused on a method of extracting a drainage network from DEMs, with the goal being the digital drainage network. Hutchinson focused on improving the DEM by actually including the drainage network in the input data for the DEM. His purpose was to create a DEM that was geomorphologically based. Jenson and Domingue described software that "conditioned" the DEM by removing pits and by more fully describing the topographic structure inherent to, but not explicitly contained in the DEM. The results of that conditioning could then be used to delineate watersheds, map drainage networks or for other geomorphic purposes.

Many other applications of DEMs in GIS analyses can be cited. Of particular interest in this research are applications of DEMs to produce viewsheds, or visibility

regions. Landscape architects have been doing visibility analysis for 30 years, with the digital applications being a more recent permutation on a long tradition (Palmer and Felleman, 1991). In one example, a DEM helped landscape architects to determine the path of a road which was not visible from a visitors' center in Great Basin National Park (Waggoner, 1989). Goodchild and Lee (1989) considered the necessary parameters to determine the best location and optimum number of fire towers required to ensure full coverage of a forested area in rugged terrain. Burrough discussed the need for estimating the visibility of a tall building in the Netherlands, where surface features, such as trees, play a more important role than does topographic variation (Burrough, 1987).

### Conclusion

In this chapter, I discussed the lack of consistent terminology surrounding DEMs. After reviewing the use of the terms DTM and DEM, I presented the concepts that will be used in this research when using those two terms. The move toward DTM systems underscores the relationship between the history of DEMs and the history of GIS. I also described various data structures used to store elevation information digitally. Finally, I stressed the importance of DEMs in GIS analysis by providing examples of DEM's usefulness in several broad classes of analysis.

Viewsheds are of particular concern in this work, and several examples were also given of applications of DEMs in determining viewshed areas. The more recent appreciation of the subtleties of the problems with error in DEMs and its effect on the

validity of results has come about as result of the combination of the applications based and the production based traditions. It is within this context that the present research falls.

### CHAPTER III DEM PRODUCTION

#### Photogrammetry and GIS

Photogrammetry is firmly behind the production of DEMs. According to the American Society for Photogrammetry and Remote Sensing (ASPRS), photogrammetry is:

the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena (Wolf 1983:I).

Mapping, especially topographic mapping, and making precise measurements have been primary functions of photogrammetrists. Assessing the accuracy of the measurements has been another important function. Analysis has tended to focus on interpretation of the resultant images. An appreciation of the need to tie data production with data use has been a more recent development.

Photogrammetry and the closely related field of surveying have been steady, if indirect, contributors to the development of geographic information systems (Burrough, 1987). One major contribution has been highly accurate mapped information and a myriad of methods to facilitate capturing and storing digital map data. Digital elevation

models have been an important component of this contribution. In addition, photogrammetry is related to remote sensing, which has contributed numerous digital analysis techniques that are useful within a GIS.

Although closely related in theory; in practice, there has been a gap between photogrammetrists and GIS analysts. Many GIS data bases, especially those intended primarily for analysis, rather than mapping, have been developed from existing maps, without the direct aid of a photogrammetric mapping firm. GIS managers frequently have not been aware of the inaccuracies inherent in this method of developing data bases. They have tended to lack knowledge of the sophisticated techniques used by photogrammetrists and of the long pursuit of accuracy in mapping by the photogrammetric community.

The data producers have also contributed to this gap. Some photogrammetrists saw the early geographic information systems as outside the realm of their concern. For example, at the DTM Symposium, sponsored by the American Society for Photogrammetry in 1978, a discussion panelist mentioned the "exotic" databases "where all possible data can be collected and organized according to their position on the Earth's surface" as an area in which "[g]eographers [were] particularly involved" (Mikhail, 1978:1488). It was not, apparently, an area in which that photogrammetrist was involved at that time.

At the same time, interest in GIS was expanding among photogrammetrists. By 1987, Merchant and Ripple wrote that "[i]t seems clear that, in the future, the interests of members of the American Society of Photogrammetry and Remote Sensing (ASPRS)

increasingly will be linked, integrated, and applied through GIS" (Merchant & Ripple, 1987:1359). The link between photogrammetry and GIS has been strengthened through 1) the entrepreneurial spirit of photogrammetric firms; 2) the ongoing need for the development of GIS data bases; and 3) the links between remote sensing and photogrammetry.

Photogrammetric firms have been increasingly aware of the financial potential of involvement in the GIS industry. They have noticed the demand by GIS users for higher quality digital maps and products such as digital orthophotography and gridded DEMs. Constantine & Trunkwalter (1991) noted that "in the early stages of GIS implementation . . . the photogrammetric community had to lobby hard to make the GIS user community aware of [their] unique role in this new field [of GIS]" (p. 44). The authors went on to challenge photogrammetrists to understand the depth of change that complex GIS data bases required in their approach to mapping "that only the rudimentary procedures are the same, and the overall data collection strategy for a GIS has become an involved and challenging, if somewhat elusive, undertaking" (Constantine & Trunkwalter, 1991:45).

The gap between photogrammetry and GIS has been bridged somewhat through the field of remote sensing. The official journal of the ASPRS is Photogrammetric Engineering and Remote Sensing. The "Remote Sensing" was added to the name in 1974 to reflect the "belief that the quantitative and qualitative aspects of photogrammetry should not develop independently, but in close coordination" (Steakley, 1975:38). The qualitative aspect was mostly interpretation of remotely sensed images. The first conference that ASPRS sponsored related to GIS was in 1981, when ASPRS co-sponsored the "Pecora

VII Symposium on Remote Sensing: An Input to Geographic Information Systems in the 1980's". The emphasis was remote sensing as data input.

Originally, remote sensing was mostly a means to acquire data. Over time, remote sensing came to signify not only data collection, but also data analysis (Colwell, 1984). Further, remote sensing has focused on raster analysis. The need to remove distortion from images, to filter out noise, and to accurately classify objects has provided the impetus to develop numerous digital and statistical tools, which today are among the important historic precedents for statistical analysis of raster data (Cressie, 1993). This tradition has contributed to the analysis presented in this thesis.

Another contribution of the field of photogrammetry to GIS has been the pursuit of accuracy and the methods used to obtain and measure it. Since GIS users are all, potentially, map creators, they can benefit from understanding error in digital maps. The photogrammetrists have been leaders in this area. The conversion to digital data has posed an important challenge to the understanding of map accuracy (Slonecker & Tosta, 1992). But photogrammetry has a long tradition of quantitative map accuracy research from which to draw. As multi-disciplinary work becomes the norm, the photogrammetrists would be logical partners in the pursuit of accurate DEMs.

Meanwhile the GIS community has been broadly aware of the issue of accuracy more recently (Goodchild & Gopal, 1989). A recent issue of The Journal of Forestry, for example, included a feature on errors in GIS (Bolstad & Smith, 1992). This article included much information that is basic knowledge to photogrammetrists. The lack of understanding of map error among GIS analysts has hindered research on map accuracy

issues in GIS, especially those issues that affect the user of the data directly. The present research helps to close the gap between data user and data producer.

### Key Factors in DEM Production

This section provides both background on DEM production and justification for the data base collected for this research. GIS data developers who purchase or produce DEMs should understand the available production options and the cost parameters involved in the decisions in DEM production. GIS analysts who use DEMs should understand the potential problems with the DEMs in their data base. The data base used for this research was intended to represent common options available to a GIS analyst in need of an intermediate-scale DEM.

The dynamic nature of the computer industry is reflected in the state of affairs in DEM production and application. With advances in computer science, the production of DEMs has evolved toward increased automation since the 1950s. Increasingly, methods have been developed that are purely digital, and sources of data have become more diverse. Softcopy photogrammetry, where all data are digital from start to finish, is an important trend (Clarke, 1990). The January, 1992, issue of PERS was devoted to articles about "Softcopy Photogrammetric Workstations". The expansion of data sources and methods of production have both contributed toward the goal of automation (Ayeni, 1982; Makarovic, 1984; Mikhail, 1978; Tewinkel, 1961).

The development of geographic information systems has served as a focal point for the integration of systems functionality required to perform all aspects of DEM

creation and use (McCullagh, 1988). Traditionally, terrain modelling has been in the purview of photogrammetrists, topographic mapping specialists, and land surveyors. As GIS analysts have required DEMs for an ever-increasing range of applications, workstation or PC-based systems have brought DEM production to the scientist's desk (Dowman, 1991; Males & Gates, 1980; McKinney, 1990). Increasingly, GISs provide functions that facilitate image processing of raster data elements. These functions include those that allow spatial interpolation from digitized contour lines, the creation of an irregular triangulated network from an altitude matrix, and visualization of three dimensional surfaces.

The changes in DEM production over the past thirty years have been profound. At the same time, certain aspects of DEM production remain important in assessing the quality of the DEMs. By quality is meant the level of detail, the accuracy, and the geometric fidelity of DEMs. Production parameters that most affect DEM quality are the scale and accuracy of the source data, the pattern, density and method of acquisition of the elevation values acquired from the selected source, and data processing, including spatial interpolation and choice of data structure to create the final elevation model. Each of these topics is discussed below.

#### Data Sources for DEM Production

While photogrammetric stereomodels collected from airborne craft are the most common source of data when new mapping is performed, other sources are also used. Ground surveys are one method to collect data directly from the earth. Alternatively,

remote systems may be used to collect elevation data. These include sonar or radar scanning and altimeters carried on aircraft (Doyle, 1978; Makarovic, 1976). Much of the equipment and methods used in DEM production have been developed for photographic sources (Wolf, 1983).

#### From photographs or maps

Helava (1978) observed that DEMs may be generated either by digitizing existing map materials or by new mapping directly from photography. New mapping, in his opinion, was the better choice in order to avoid the pitfalls associated with the unequal or unknown quality of existing maps. On the other hand, when map quality is relatively high and well known, the decision to use existing maps may be well justified. The United States Geological Survey, in its national program of 7.5' DEM creation, has changed from using photographic stereomodels for DEM productions to digitizing the contours from existing maps. This has proved to produce more accurate DEMs at a 30 meter resolution than the photographic sources in use since the 1970s (Allder, 1983; Clarke, Gruen & Loon, 1982a; Kumler, 1992; USGS, 1990).

Topographic maps at a variety of scales provide a rich source of elevation information. In order to capture the data and produce a DEM from it, the lines must first be digitized and then an interpolation procedure applied to fill in information between the contour lines. Digitizing contours manually is tedious, difficult, and prone to error. The amount of labor involved commonly makes it prohibitively expensive. Use of digitally scanned contour data is often the most reasonable choice when creating a DEM from

contour lines (Doyle, 1978). Hydrographic information and spot elevations provide further detail for inclusion in the DEM prior to interpolation.

#### From digital images

Since the late 1950s, automated photogrammetric systems have been analogue, digital or a mixture of the two. All-digital photogrammetric systems have been in use since 1976 (Makarovic, 1984). Full automation of the techniques using digital data still presents some difficulties and research has continued to focus on ways to make data capture and processing more efficient and reliable in a variety of conditions.

A fully digital and automatic system requires digital input. Digital images may be created in several ways. With a digital camera, images may be captured directly from the earth in digital form. This technology has advanced to a point where the images that are captured by digital cameras are metrically useful (Stefanidis, Agouris & Schenk, 1990). Digital images may also be created from film images through automatic digital scanning of photo image densities. Scanning microdensitometers record and store in digital form the grey tones on the film (Wolf, 1983). A third form of digital image may be acquired through a variety of multi-spectral or panchromatic scanners that sense the emitted and reflected properties of objects and record them in digital form. These scanners may be loaded on both air- and spacecraft.

Satellite image stereopairs are relatively new sources of data for the production of DEMs (Konecny et al., 1987; Raggam, Buchroithner, & Mansberger, 1989; Rodriguez et al., 1988). DEMs produced from satellite image stereopairs are relatively cheap when

large, remote areas require mapping. Stereopairs can be created conveniently from SPOT imagery.

The French satellite, SPOT, produces panchromatic images at a 10 meter resolution. When two images are taken of the same area from appropriate angles and widely separated positions, it is possible to apply modified photogrammetric techniques to the images. SPOT imagery is especially appropriate for the collection of imagery for stereo viewing, because the satellite's sensor can be pointed to the side of the orbital path, to provide a side-looking view. This makes it possible to view the same area on the earth's surface from different perspectives. Thus, SPOT imagery can be used to produce stereopairs for DEM production similar to those based on aerial photo stereopairs.

#### Mapping Scale and DEM Resolution

The map scale of the DEM data source is important whether the methods and images are digital or not. A large scale source is required for a highly accurate and detailed DEM. It can be confusing when comparing sources where "scale" has different implications. The scale of aerial photography, for example, must be considered in light of the fact that it may be magnified under zoom optics, thus allowing considerably more detail to be seen in the photos than was available at the smaller scale. A hard copy map, on the other hand, is much more static. Enlargement will not change the data content of the map.

The proper relationship between the horizontal resolution of the DEM and the map scale of the data source has not been resolved in a systematic manner. The analogous

situation in traditional topographic mapping are the related issues of contour intervals and map and photo scales for a mapping project. Appropriate mapping scale for topographic mapping from aerial photography depends on a variety of factors. These include the instruments used, the type of terrain, and the accuracy requirements.

The resolution of a DEM would involve similar considerations, with the important addition of data storage. The cost of setting too high a resolution is disk overhead and memory usage. The cost of using too low a resolution is lack of possibly critical detail (Aronoff, 1982a; Mitchell, 1981). The major source of available information on the issue comes from common practice. Here are two examples. The USGS has used 1:80,000 scale photography to produce 30 meter resolution DEMs. They have also used larger scale photography at 1:40,000 for 30 meter DEMs, they and have digitized contour lines from 1:24,000 scale maps for the same type of DEM (USGS, 1986, 1990). In mapping project which resulted in the creation of reference DEM used for this research, 1:24,000 photography was used for mapping at 1:4800 scale. The DEM produced from that project from the same photography had a 10 meter resolution. The decisions leading up to the setting the proper relationship between mapping scale and DEM resolution varies with the quality of the photography and the type of terrain. It is also a somewhat subjective process.

#### Spatial Sampling for DEM Production

In addition to the scale and origin of the data source, the decisions about the spatial properties of the points to use as reference data for DEM production play a key

role in the accuracy of the final DEM. The density and location of elevation values collected will affect the accuracy and level of detail (map scale) of the final DEM. The decisions about density and spatial location of reference points should be appropriate for the type of interpolation and the instruments used to collect the data, as well as the terrain characteristics. In addition, they should minimize operator fatigue and the cost of production. Li (1990) has provided an excellent review of sampling strategy and its importance in DEM construction.

The sampling of terrain information for the creation of a terrain model is a special case of sampling. Unlike most other phenomena, it is possible to know almost everything about the population from which the sample is taken. The problem is in the understanding of the surface from which the sample is taken so that when the reference points are used to produce a DEM, the resultant DEM is a valid rendition of the earth's surface. Economy is important. Spatial sampling decisions greatly affect the time required to create a DEM. The cost of data acquisition is the largest part of the cost of DEM production (Stefanovic, Radwan & Tempfli, 1977). From a technical standpoint, the primary function of the original elevation points cannot be understated. As Chapman noted (1987:42-43), "geometric fidelity can only be achieved by acquiring [elevation data] at appropriate locations. More specifically, this implies that the form, character and other geometric qualities of the terrain must be captured in order to convey a 'true' picture of the landscape." Ackerman (1980:2) concluded that "[t]he primary factor deciding the attainable accuracy of a [DEM] is data acquisition."

### Photogrammetric methods

For photogrammetric data acquisition, the pattern of the reference points is either random, at nodes on a grid, or in the form of contours, profiles, or other morphological lines and points (Stefanovic, Radwan & Tempfli, 1977). The most suitable pattern is dictated by the application intended for the DEM, the type of terrain and various operational questions, such the necessity of speed and the need to minimize operator discomfort. Generally, there is a yet unresolved debate in the field over whether it is better to sample carefully selected highly accurate points or to collect enormous numbers of points of lower accuracy, and discard those which do not meet required standards (Ackerman, 1980).

Closely related to the pattern of the reference points is the density of the points. Makarovic (1973, 1976, 1979) has examined automated methods of determining optimal elevation samples. A major goal of his research has been to achieve fully automated data acquisition that preserves geometric fidelity. He proposed the use of progressive sampling, whereby points are sampled in a coarse grid, which is then refined in areas of greater relief roughness until a specified accuracy is attained. This strategy tends to over-sample places with abrupt changes in the terrain. It can be improved by first selectively sampling places where the terrain makes an abrupt change and then using progressive sampling on the rest of the area.

Ayeni (1982) compared seven sampling schemes based on the well known classifications of random, stratified and systematic sampling patterns. He used a measure of terrain roughness to determine the optimal sample size, using a parameter that

incorporated roughness of one area as a compared to the entire area. With all of the terrain types that he tested, the "unaligned systematic stratified random" pattern proved, overall, most efficient (see Ayeni, 1982:1694 for a description).

Balce (1987) compared four different computer programs designed to determine the optimal sampling interval of reference points from photogrammetric sources. He found that in rough terrain, any of the four programs was suitable. In fact, though the programs exhibited systematic tendencies to over or under sample in certain conditions, the differences in the results of the different programs was small enough that any of them could be defended. The one program that performed slightly better, overall, was based on the concept of self-similarity. In areas where elevation values are the similar to each other, less sampling needs to be done to get adequate data to represent the area.

#### Automated methods

When DEMs are created with automatic correlation techniques from digital imagery, the elevation reference points are usually collected in "patches" (Panton, 1978; Hannah, 1981; Vincent, Pleitner & Oshel, 1984). These are small areas of the left and right stereo images for which the same features may be identified automatically on both of the two images. Once this correlation has been achieved, the calculation of the elevation of points within the patch may be made. The patches vary in size depending on the quality of the image, the features available to make the correlation between images possible, and the roughness of the terrain.

Sampling schemes are less important when the cost per point of data collection is low. This is the case with the automatic methods using digital input. In this case, it is

common to calculate pixel by pixel height values and then get rid of those that are obviously in error. For example, a single pixel that has a z value that is dramatically different from its neighbors would be suspect. When automatic image correlation techniques are used, the spot size selected for digital scanning of photographic images impacts the density of subsequent elevation sampling. A photograph at a scale of 1:68,000 scanned with a 30 micrometer (photo measurement) spot size yields a digital image with a 2.04 meter (ground measurement) pixel size. Elevation samples taken from the digital stereomodel will be limited by the density of the pixels in the imagery. Likewise, a satellite image stereomodel with a pixel size of 10 meters (such as SPOT panchromatic imagery) will provide elevation detail only to the extent possible given the detail in the imagery.

#### Data from existing maps

When the data are acquired from an existing map, they are often in the form of contour lines supplemented by spot elevations. An alternative to this is to overlay manually, a regular grid on the topographic map. Then, reference elevations may be estimated visually from the map at the intersections of the grid lines. The directional pattern of contour lines can make interpolation more difficult, so the use of a grid is better in some cases (Wood & Fisher, 1993). On the other hand, the grid method requires a person's subjective effort, and cannot be automated, as can the digital tracing of existing contour lines.

### Spatial Interpolation

Interpolation is a means to estimate unknown values using the information from known points. Spatial interpolation is the "estimation of surface elevations in areas with data values nearby, on more than one side" (Monmonier, 1982:199). The known points are often called "reference points." Two items are important with regard to spatial interpolation and DEMs in the present context. These are the role of interpolation and the choice of method of interpolation.

First, in terms of the quality of DEM, the role of the method of interpolation is secondary to the role of the density and accuracy of the original elevation values sampled from the source data (Weibel & Heller, 1990; Yoeli, 1984). "Even the simplest interpolation method is useful if the density of reference points is sufficiently great" (Schut, 1976:390). On the other hand, a complex interpolation routine is not a magic cure for insufficient original data.

Though secondary to data sampling, interpolation still plays a role in DEM quality. Thus, the second issue is the question of the differences among interpolation methods and their relative suitability for DEMs. Monmonier noted that "[i]nterpolation is a highly subjective process, and an estimation procedure is not right or wrong, but merely plausible or absurd" (Monmonier, 1982:61). Thrall and his colleagues provided an empirical example of the effect of using different types of interpolation on the same reference points (Thrall et al., 1993). Methods of interpolation abound, but they are not all equally suitable for DEM production. Some, such as the areal methods, for example, are geared toward data stored as polygons, which is often the case of data on socio-economic topics.

They are not useful in the case of topography (Lam, 1983). Yoeli (1984) discussed some differences between surface models of earth elevation and surface models of other thematic features.

Over the past several decades, a vast body of literature, from numerous academic fields, has developed covering the question of spatial interpolation. These have included the fields of photogrammetry, remote sensing, cartography, geography, geostatistics, statistics, and computer science. The related topics of triangulation, spatial smoothing and spatial filtering could be included to expand the possibilities still more. The present discussion has been narrowed considerably by taking into account only those methods used for creating a grid DEM from reference data.

Reviews of interpolation methods have focused on several areas, related to, or dealing directly with, DEMs. Leberl (1975) considered interpolation in the broader context of photogrammetry, with DEMs being one major component. Schut (1976) provided the best review of methods designed specifically for DEM production. Though many individual interpolation methods have been documented since Schut did his work, his framework (presented below) is still useful to place even the newer methods in context. Lam (1983) was concerned with cartographic interpolation, and contours were the output from the methods she described. The grid DEM was an intermediate product in many of the methods included in her review. Burrough (1987) also provided an important review in his chapter on interpolation methods. Though set in the context of GIS in general, rather than DEMs in particular, Burrough's assessment of such factors as

the assumptions, the computing load, and limitations of various interpolation methods is useful in choosing appropriate methods.

From a practical view, the method of interpolation needs to match the form of the reference data. Reference data may be randomly distributed in space, they may fall along contour lines, or they may be in some other regular pattern. Elevation values in a random pattern could be considered the dominant form of reference data for a DEM. Many point methods, such as defined by Lam in her review, may be applied to random data points. Schut also distinguished between those methods that are best used for random points or for other patterns. A second important pattern is a set of digital contour lines. This is a form of data of special interest to the GIS analyst who wishes to create a DEM from paper maps. Schut discusses some methods to do this. Several other authors have written of issues related to interpolation from digital contour lines (Wood & Fisher, 1993; Craig & Adams, 1991; Yoeli, 1984; and Clarke, Gruen & Loon, 1982b).

One difficulty facing the GIS analyst who wants to better understand the role of interpolation in a particular DEM is lack of information about the available interpolation programs. Programmers who write interpolation algorithms do not necessarily read the academic literature, and it is usually up to the user to relate the actual algorithm to the various frameworks. Programmers also do not always document the procedure used for the program. Two examples illustrate some of the problems.

Kumler described his attempt to determine the interpolant used in the LATTICESPOT program (Environmental Systems Research Institute, Redlands, California). He found that the number of points from which the interpolation was

performed was not clear and that the ESRI technical staff could not provide complete information. He concluded that what he had been told about the interpolant did not appear to be true and that his tests showed "evidence of something very mysterious" (Kumler, 1992:81).

In another example, Fandrich (1995) related her attempts to understand the output of the kriging interpolation option used in the PC-based SURFER program (Golden Software, Golden, CO) program. Kriging is a powerful estimation tool developed and applied mostly in geostatistics (Isaaks & Srivastava, 1989; Journel, 1986; Burrough, 1987). One important characteristic of kriging is its ability to answer the question "what are the errors (uncertainties) associated with the interpolated values" (Burrough, 1987:155). The SURFER kriging output does not include this error estimation. Without the error estimation map, the value that kriging offers is seriously lessened.

### DEM Production at the USGS

The U.S. Geological Survey National Mapping Division distributes various digital map products, including DEMs. It is one of the major producers and suppliers of DEMs for use in GISs in the United States. As such, the USGS has set a standard against which other products are compared. The USGS distributes several different gridded DEM products, each comparable in coverage and detail to an existing USGS map series. They also distribute digital contour lines as Digital Line Graphs (DLGs), which are digitized from 1:24,000 scale maps.

The largest scale USGS DEM is distributed in coverages and detail similar to the USGS 7.5' map series (USGS, 1990). Alder (1983) summarized the development of this product at the USGS. The first DEMs, produced in the early 1970's were related to orthophoto production. The z-values required to make the orthophotos were saved, in digital form, and were the basis of the first USGS grid-DEMs. During the 1970s, USGS developed a standard format for grid-DEMs, which is still in use today.

The USGS 7.5 minute DEMs provide elevation estimates in a grid pattern with a 30 meter horizontal resolution. The primary source of data for the early 7.5' DEMs was aerial photography from the National High Altitude Photography program (NHAP). Larger scale aerial photography and DLG contours are used for DEM production currently.

Four methods have been employed in the collection of elevation points for the 30 meter USGS models (USGS, 1986). The USGS has made extensive use of the Gestalt Photomapper (GPM-2). This instrument allowed automatic correlation of the stereo model for one patch at time (Allam, 1978). The patch size varied with the terrain, with larger patches for flatter terrain. Photogrammetric profiling was another early method of USGS DEM production. Profiles, or regularly spaced rows of elevation points, were collected from aerial photography using stereoplotters.

Though the vast majority of USGS 7.5' DEMs have been produced by either manual profiling or with the GPM-2, more recently produced USGS models have been created using interpolation from digital contour lines. The contour lines have been digitized photogrammetrically or have been digitized from existing 7.5' maps. The

contour to grid interpolation procedure, CTOG, was developed to interpolate a regular grid from digitized contours. These later DEMs are of better quality than the early ones, but are also more costly to produce (Kumler, 1992).

This chapter has outlined the relevant pieces of a vast body of literature related to DEM production. Photogrammetry has been a key component in the roots of DEM production, but the trend recently has been to diversify. Methods of data capture, processing, and analysis as well as sources of data have been developed for and by a broad community from various disciplines. GIS has been the impetus behind this expansion. The USGS has been an important player in the development of DEMs for the GIS marketplace, so a section of this chapter outlined the DEM program at the USGS.

## CHAPTER IV ACCURACY OF DEMS

### What is Accuracy?

Accuracy implies a conformity to true values. Accuracy of a DEM is expressed by some measure of the degree to which the values in the DEM reflect true ground values. When elevation values are not accurate, they contain error. In terms of GIS analysis, the result of a system query supplies the user with estimated elevation values. Error is measured as the difference between the values generated by the system and the true values on the ground (Goodchild, 1990). In the present research, truth is represented by the reference model. Error is the difference between values in the test models compared to values in the reference model.

DEM error has been classified in several ways. The USGS classifies DEM error as systematic, random or a blunder (USGS, 1986; Wolf, 1983). Systematic error occurs in a pattern related to some aspect of the production process or the natural phenomenon measured. Random error is unpredictable and generally a small part of overall error. Blunders are often large and usually obvious, and relatively easy to correct.

The spatial distribution of systematic error, in some cases, can be measured, and thus, corrected. Often, however, systematic error is very complex, making a global

correction impossible (Hannah, 1981). Random error is normally distributed, so the positive and negative errors tend to compensate for each other when measured globally. Large blunders should not pose any great problem with DEMs, because with adequate post-production editing of the DEM, blunders, as defined above, should not be present in the final DEM (Ackermann, 1982). Blunders that result in error of a lesser magnitude are more insidious and are very difficult to detect or correct.

Horizontal and vertical accuracy of DEM data are separate concepts. Horizontal error results in *z* values that are misplaced in space, but are accurate relative to each other. Vertical error implies that an elevation value is correctly located planimetrically, but is not the correct height. However, in terms of DEMs, "an implicit link exists between horizontal and vertical accuracy wherein the predominate measure of accuracy is represented almost totally by tests of the vertical dimension" (USGS, 1986: 2-4). Virtually all work related to DEM height accuracy has dealt with vertical accuracy (Li, 1990).

Accuracy and scale are closely related in cartography. Map scale is a measure of the relationship between map distance and ground distance. The National Map Accuracy Standards (NMAS), written in the 1940s, focused on acceptable amounts of error in various scales of topographic maps. To meet the NMAS, it is necessary, for example "that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval" (U.S. Bureau of the Budget, 1947). The contour interval is closely associated with the scale of the map. Selection of the contour interval for a project is an important part of the "art" of map making (Wolf, 1983).

The NMAS have proved to be inadequate when dealing with digital products (Slonecker and Tosta, 1992). For example, how does a contour interval relate to a gridded DEM produced from satellite imagery? Intuitively, the detail present in a satellite image and the potential information content in the image are related to the scale of a map produced from the image. The conceptual understanding of digital map data has lagged behind the technology that has radically changed spatial information handling. Some recent initiatives have made progress in this area, notably, the Spatial Data Transfer Standards of the U.S. National Institute of Standards and Technology. To date, however, there is not a straight forward, commonly used formula to express quantitatively the accuracy standards for digital map products.

For a given area, and assuming proper production standards, larger scale DEMs will provide more information, and will be more accurate than smaller scale models. Large scale DEMs are not necessarily the solution to solving the problem of accuracy, however, since data storage and handling costs are major issues with data-intensive grid DEMs. Intermediate scale DEMs of the sort tested here are useful when used within their intended context. The emphasis in this research is not quantity of error, but rather the result of that error and the usefulness of the DEM for a particular purpose. The American Congress on Surveying and Mapping's National Committee for Digital Cartographic Data Standards emphasized that "the foundation of data quality is to communicate information from the producer to the user so that the user can make an informed judgement on the fitness of the data for a particular use" (Chrisman, 1984:81).

### Fractals, Scale and DEM Accuracy

Mandelbrot's (1983) theory of fractals is an important thread in DEM research papers. It has a logical place in a discussion of error in DEMs. The fractal dimension (D) of a topographic surface is between the Euclidean dimensions of 2 and 3. The dimension increases with increased roughness, and has a linear relationship to roughness as perceived subjectively (Pentland, 1984). An important characteristic of a fractal surface is that it is self-similar. A surface (or line) is self similar "if any part of the feature, appropriately enlarged, is indistinguishable from the feature as a whole" (Goodchild & Mark, 1987:268).

If the fractal model is appropriate for a topographic surface, then map scale ceases to be an issue. The characteristics of the original DEM could be applied to a subsection of the model and it could essentially fill in the pieces required for an enlarged view. This was the approach of Yokoya and his colleagues (1989). But the random element introduced to the simulated portion, usually through a fractional Brownian motion (fBm) model can never replicate terrain. Terrain surfaces have trends which pose a major problem for the fractal model.

Currently, the theory and methods surrounding the use of the fractal model for topography are in flux. When Polidori, Chorowicz, and Guillande (1991) assumed the validity of the fractal model (using the fBm model) of terrain in assessing interpolation error in a DEM, Goodchild and Tate (1992) objected. They questioned the authors' conclusions that a difference in the estimate of D at different spatial lags implied evidence

of error in the DEM. "The authors . . . assume that the real surface is characterized by fBm despite the fact that there is ample evidence in the literature that real topographic surfaces are not perfectly modeled by fBm and, more seriously, without knowledge of how much their surface deviates from fBm" (p. 1569).

Michael Goodchild has led geography in questioning the usefulness of fractals to model real terrain. In addition, he has questioned the existence of self-similarity in many cases. More than a decade ago, Goodchild (1980) was critical of earlier work by Richardson (1961) which focused on line length, map scale, and the concept of self-similarity. "Although Richardson's data clearly support the existence of self-similarity, in reality the application of the concept to the natural terrain is limited" (Goodchild, 1980:87).

Goodchild established two major problems with fractal theory and DEMs. One is with the measurement of the fractal dimension. Estimates of  $D$  using different estimation methods on the same DEM, yield different results and are sensitive to the type of terrain being measured (Klinkenberg & Goodchild, 1992). A second problem is with the assumption that a stochastic model is appropriate as a model of terrain. Others have echoed this concern, among them Xia, Clarke and Plews (1991) who found that among the 200 DEMs that they measured, "very few . . . [were] truly self-similar and the fractal model is only applicable to most data sets within limited scale ranges or in certain directions" (Xia, Clarke, & Plews, 1991:336).

The fractal model has been useful to create realistic simulated terrain, and it can be useful to distinguish among certain geomorphic structures, but it should be used with caution as a model of real terrain. Goodchild and Mark (1987:275) concluded that:

The fractional Brownian process has been used as a convenient way of generating self-similar surfaces, and certainly such surfaces more closely resemble some types of real topography than do the results of any other available method of simulation. We have argued that ... fBm offers a unique tool to geomorphology as a null hypothesis terrain. Its self-similarity gives it the appearance of rawness or lack of geomorphic modification, suggesting further application as an initial form for simulation of process.

In spite of its currency, the question of the applicability of the fractal model to topography is sufficiently great to warrant an entire separate line of research to establish the degree to which a fractal model is appropriate for real terrain. This task is left to others. This thesis is concerned with the error in a particular set of DEMs, and since a complete reference set of higher quality is available, there is no need to simulate reference data. Of some related interest is the question of the difference in the estimate of the fractal dimension when DEMs are created by different methods. Estimates of  $D$  are sensitive to data and methods of analysis, so it is possible that the subtle patterns of error in DEMs is responsible for some of the variation measured by  $D$ . This is an item of potential future research.

### Spatial Autocorrelation and DEM Accuracy

Spatial autocorrelation is another important topic in DEM research. "Spatial autocorrelation exists whenever a variable exhibits a regular pattern over space in which

its values at a set of locations depend on values of the same variable at other locations" (Odland, 1988:7). This concept is often called spatial dependence. The term "correlation" as used commonly in statistics is most often in reference to the co-relation of two variables. Autocorrelation, on the other hand, occurs when a single variable is related to itself when pairs of observations are compared with each other. Griffith concluded that spatial autocorrelation (SA) is "the relationship among values of some variable that is attributable to the manner in which the corresponding areal units are ordered or arranged on a planar surface" (Griffith, 1987:11).

Spatial autocorrelation may be positive or negative. With positive autocorrelation, like values tend to cluster. With negative autocorrelation, values are found predominantly near unlike values. Positive autocorrelation is the most common case, and all subsequent discussion of SA may be assumed to be about positive SA.

Spatial autocorrelation is important to a study of error in DEMs for at least two reasons. First, is the question of violation of the assumption of independence required of variables used with inferential statistical methods. If this assumption is not met, then certain parameters, in particular the standard error estimates used in hypothesis testing, will be biased (Odland, 1988; Clark & Hosking, 1986; Griffith, 1992). Interpretation of linear regression involving geographic data should take into account this potential factor in order to avoid errors in hypothesis testing.

Spatial autoregressions are a common topic in discussions of statistics that address issues related to spatial data (Ripley, 1981; Clark & Hosking, 1986; Cressie, 1993). As Odland (1988) explained, the result of spatial dependence in variables used for regression

analysis is that the values of tests of significance of the regression coefficients are inflated. This could lead the researcher to mistakenly believe that variables are related, when in fact, they are not (Type I error). The way around this is to include a spatial term in the model. An example of this approach is found in Griffith (1992).

A second reason that SA is important to a discussion about DEM error is that it is a way to express quantitatively the degree to which a variable is clustered in space. Neither the mean nor the standard deviation can express this. When a description of the pattern of the data is the goal of the research, the SA is not a problem, it is a variable of interest. Congalton (1988a) provided a good example of the use of SA to describe a pattern of error in image classification. He used an SA measure to express, quantitatively, the different patterns of error in image classifications for landcover with different spatial characteristics.

### Ways to Assess DEM Accuracy

Given the complexity of issue of error in DEMs, it is not surprising that numerous methods have been employed to assess the error and, in turn, to judge the quality of a DEM. In addition to the (questionable) fractal method just discussed, the methods have included visual assessment, measurement of root mean square error, and assessment of measurable derivative products such as a drainage network or viewshed.

### The Root Mean Square Error

The most common measure of accuracy of DEMs is the Root Mean Square Error (RMSE) (Li, 1988). This is a measure of the difference between discrete elevation values estimated by the DEM and the value of the true elevation at those points (Table 4-1). The USGS employs this method and reports the RMSE for the DEMs that have been thus assessed in the header file of DEM digital products (USGS, 1990). The USGS classifies their DEMs according to the accuracy thus measured.

| Table 4-1<br>The Root Mean Square Error                             |                                                                                                              |
|---------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|
| $RMSE = \sqrt{\left( \frac{\sum_{i=1}^N (Z_t - Z_c)^2}{N} \right)}$ |                                                                                                              |
| where                                                               | $Z_t$ = the value of a test value cell<br>$Z_c$ = the value of a control value cell<br>$N$ = the sample size |

Based on the RMSE calculated from at least 28 test points, USGS 7.5 minute DEMs are divided into three different accuracy levels. The lowest level is level 1, for which 7 meters is the target RMSE. DEMs produced with high altitude photography (1:40,000 scale or smaller) and DEMs acquired photogrammetrically with manual profiling or the GPM-2 are restricted to level 1. This includes almost all DEMs available currently (USGS, 1990:15). Level 2 DEMs are produced by interpolation from contour lines digitized from air photos or hardcopy maps. Following the NMAS convention of

linking contour interval with accuracy, level 2 DEMs must have an RMSE within one-half of the contour interval. So, a DEM interpolated from two meter (6.56 feet) contours should have an RMSE of one meter or less. Level 3 DEMs should have an RMSE of less than one-third of the contour interval.

The RMSE estimates of DEM accuracy have three weaknesses. First, in a statistical sense, the RMSE calculated from a discrete set of check points is not sufficient. Li (1991) demonstrated that the reliability of the RMSE measured at discrete points was related to the location, accuracy and number of control (check) points used in calculating the RMSE. The number of control points required to get a reliable RMSE was related to the amount of variation of the difference in elevation between the predicted and expected values. Li recommended that the location of check points should be a random distribution of points. He also noted the need "to extend [DEM accuracy] analyses to a complete surface" (Li, 1990:7).

The second weakness is that while the RMSE tells something about the overall magnitude of error, it does not give information about the error in slope calculations. Slope, or steepness of the terrain, is frequently more important to GIS analyses than is absolute elevation. Goodchild noted that "to know the reliability of estimates of slope and other parameters, we must have knowledge of the spatial dependence of error, particularly between adjacent measurements in the DEM" (Goodchild & Tate, 1992:1569). The third weakness of the RMSE when calculated from a limited number of points, is that it is not able to detect horizontal shifts in the DEMs. The question of horizontal error, which is very difficult to detect, was not considered explicitly in this research. An assessment was

made, however, of the potential for a regular, and relatively obvious shift in the test DEMs, compared to the control DEM. This was done by selecting a set of profiles, extracting the elevation values from each of the DEMs, and plotting the elevation values, using a spreadsheet graphics option. None was apparent in these tests.

In the current research, these two weaknesses of the RMSE were virtually eliminated through the availability of a control DEM which provided true elevation values for the entire study area, not only at discrete points. An additional weakness of the RMSE became apparent in the course of this research. The difference between the true value (in the control) and the estimated value (in the test models) is the basis for the RMSE. For individual cells, this may result in negative numbers, which are unwieldy for some statistical analysis. Logistic transformations, for example, are not possible on negative numbers. To overcome this problem, I used the ratio between the control and the test values calculated for each cell to measure the magnitude of the error in the test DEMs.

The use of such ratios is documented in social science research. The use of ratios in the real estate/public finance and urban geography literature is most relevant to this dissertation. One frequently used application is in the calculation of the ratio of assessed value (the estimated value) to the market value (true value) of housing. Davies (1978) provides a good summary of the literature on property tax assessment quality, particularly ratios of estimated to known, or true, values. Also see Thrall (1979a, 1979b).

The test DEMs are analogous to the assessed value and the control DEM is analogous to the market value. The estimate may be made for individual pixels, the mean

control-test (EVTV) ratio for subregions can be calculated, or a root mean square error may be calculated from the ratios. The mean EVTV ratio, expressed as a percentage is calculated by dividing the ratio by the sample size and multiplying by 100 (Table 4-2). The multiplier of 100 is used to minimize rounding errors common with computers and small decimal values. It also makes the resultant calculation more intuitively interpretable.

| Table 4-2<br>The Estimated Value True Value Ratio            |                                                                                                        |
|--------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|
| $MeanEVTV = \frac{\sum_1^N (\frac{Z_t}{Z_c})}{N} \times 100$ |                                                                                                        |
| where                                                        | $Z_t$ = the estimated (DEMT) cell value<br>$Z_c$ = the true (DEMC) cell value<br>$N$ = the sample size |

It was necessary to measure the magnitude of error in the test DEMs using ratios in a manner similar to the way the RMSE was calculated (Table 4-1) for differences. This was accomplished by calculating the root mean ratio squared error (RMSRE). Table 4-3 shows the calculation for the root mean square ratio error. The RMSRE measures the average absolute difference of the test model values from the control model values. A value of 100 for EVTV indicates that the estimated and true values were the same. Thus, the difference between the EVTV and 100 is calculated for

each grid cell. The square root of squared average difference of the EVTV from 100 is the RMSRE.

| Table 4-3<br>The Root Mean Square Ratio Error                 |                            |
|---------------------------------------------------------------|----------------------------|
| $RMSRE = \sqrt{\left( \frac{\sum (EVTV - 100)^2}{N} \right)}$ |                            |
| where                                                         | EVTV = the cell EVTV ratio |

### Visual Assessment

A visual assessment of shaded relief renditions of DEMs provides valuable insight into the nature of DEM error. An example of a shaded relief map is provided in Figure 6-1. Acevedo (1991), for example, assessed USGS 30-minute DEMs in this way. An image of the 30-minute DEM compared with one from a 1-degree DEM of the same area clearly demonstrated the difference in detail in products of different scales. Artifacts introduced from the gridding routine were also apparent, appearing as "flattopped ridges and valleys" (Avecedo, 1991:7) in the 1-degree product. Interpolation in flatter areas created visible artifacts in the 30-minute DEMs.

Wood and Fisher (1993) took a more structured approach to using visualization to detect errors in DEMs. Their work was of particular interest in the current context because they focused on the differences in the pattern of error in DEMs related to the different interpolation algorithms. They created their DEMs through interpolation from

digital contour lines, using four different interpolation methods. They also noted the deficiency of knowing only the RMSE in terms of assessing the usefulness of a DEM for a particular application. The major thrust of their work was to illustrate how viewing the maps of shaded relief, aspect, the result of an edge detection filter, and profile convexity all revealed artifacts of the interpolation process that would otherwise be hidden.

### Error in Derivative Products

Another way to assess the quality of a DEM is to measure the error in a product derived from the DEM. Many applications of GIS are quite complex, and the propagation of error from the data to the final product is equally complex (Heuvelink, Burrough, & Stein, 1989). Fisher (1992) considered the effect of DEM error on the calculation of viewsheds and Lee, Snyder and Fisher (1992), its effect on floodplain delineation. Both of these projects involved using a USGS 7.5-minute DEM, to which random and systematic error was added in a controlled manner in order to assess its effect on the derived product. The original DEM was used as the control. In both cases, the addition of error within a threshold of 7 meters was found to have a significant effect on the validity of the products derived from the DEMs. The magnitude and pattern of the error should be considered when evaluating the result of a GIS procedure using DEMs.

Fisher's (1992) work on viewshed uncertainty was especially important as a precedent for the current research. The major thrust of his work was to test the null hypothesis that "the viewshed area in the original DEM is not a member of the set of viewshed areas in elevation models generated by [a perturbation algorithm]" (Fisher,

1992:1323). The original DEM represented truth, or reference data. His basis for inclusion in the original viewshed was comparing the number of cells in the viewsheds from 19 realizations of the perturbations with the number determined by area, or number of cells, of the viewsheds.

This method of determining inclusion in a set of viewsheds is expedient, but imperfect. The method used in this dissertation allows a full accounting of type of error (see next session for a discussion of this) and thus leads to a better understanding of the error in the viewsheds.

A second important aspect of Fisher's work was his preliminary analysis of determinants of viewshed error. He used correlation analysis and stepwise regression to assess the ability of the elevation of the view point and the minimum and maximum elevations within 1000m (a measure of terrain roughness) of the view point to predict viewshed area. The elevation of the view point was the only variable with predictive power. He also observed that more spatially autocorrelated error seemed to produce a better rendition of the viewshed.

### Error in Cell Classifications

The process of producing a viewshed from a DEM is, in essence, a matter of classifying cells as visible or not visible. Raster image classification is an important component among space remote sensing techniques. Satellite images need to be classified in order to be useful in quantitative analysis. A cohesive set of literature has accrued over the past 15 years concerned with the error in image classifications (Aronoff, 1982a, 1982b, 1985; Congalton, 1988a, 1988b, 1991; Rosenfield & Fitzpatrick-Lins, 1986; Story

& Congalton, 1986). One particular thread of that research is related to the use of error matrices, or contingency tables, which have now become a standard part of remote sensing (Lillesand & Kiefer, 1987). The understanding of error gained from the experience in image classification is applicable to better understanding the accuracy of viewsheds derived from grid DEMs.

The recent review by Congalton (1991) provides an overview of the problems associated with accuracy assessment of remotely sensed data. The error matrix is a key to the concepts described in the review (Figure 4-1). In an error matrix, the reference data occupies the horizontal axis and the test data, the vertical axis. The diagonal cells indicate the number of cells properly classified. The cells off the diagonals indicate the number of cells misclassified and also provide the user with information on how the misclassification came about. In the case of viewsheds, for example, a visible area may have been classified as not visible or vice versa.

The overall accuracy of the classification is the sum of the properly classified cells divided by the total number of cells (Figure 4-1). The value is usually expressed as the percent correct. Additional information can be found by using the row sums and the columns sums and determining the percent correctly classified as a particular group, e.g. the percent correctly classified as visible. The classic article by Story and Congalton (1986) illustrated that the diagonal divided by the row sum measures errors of commission, while the diagonal divided by the column sum measures errors of omission.

|             |             | Visible | Not Visible |     |                                                                                                     |
|-------------|-------------|---------|-------------|-----|-----------------------------------------------------------------------------------------------------|
| Not Visible | Visible     | 29      | 16          | 45  | Total Accuracy<br>$(29 + 184)/300 = .71$<br>Errors of Omission<br>$29/100 = .29$<br>$184/200 = .92$ |
|             | Not Visible | 71      | 184         | 255 | Errors of Commission<br>$29/45 = .64$<br>$184/255 = .72$                                            |
|             |             | 100     | 200         | 300 |                                                                                                     |

*Values are in numbers of cells*

Figure 4-1  
Error Matrix

An analogy illustrates the significance of omission and commission errors in terms of viewshed errors. In a court of law, the witness is asked to tell the:

- 1) the truth -- overall accuracy
- 2) the whole truth -- no errors of omission
- 3) and nothing but the truth -- no errors of commission

Overall accuracy does not distinguish among the sorts of error that might occur. Using the example from Figure 4-1, the overall accuracy is 74%. But not only do we want to know if an answer is "true," we also want to know that we have the **whole** truth. How much of the visible area was omitted from the viewshed? In some cases, cells that should have been included in the visible area were classified as not visible, and some not visible were classified as visible. These would be called errors of omission. The column totals and the diagonals allow us to calculate that errors of omission resulted in only 29% of the

truly visible region as being properly classified. At the same time, 92% of the truly not visible region was classified correctly.

Now, consider errors of commission. We also want to know that the truth is not mixed up with some "untruth." With the viewsheds in Figure 4-1, some of the area that was classified as visible, was actually not visible. Using calculations from the row totals and the diagonals, 47% of the area identified as visible, was truly visible. Of the area identified as not visible, 87% percent was truly not visible.

The distinction between errors of omission and commission is especially important in terms of evaluating DEMs according to their suitability for a particular application. For example, the Forest Service might be concerned with protecting scenic views from logging activity. From the point of view of the Forest Service, the viewshed calculation should be relatively free from errors of omission in terms of the visible area, i.e. all the visible area would be included within the viewshed. If some of the area classified as visible was actually not visible (an error of commission), that would present a problem only insofar as the logging company might be concerned, since some trees that could have been safely logged were excluded.

### Error in DEMs from Various Production Methods

#### Error in Photogrammetrically Sampled DEMs

The instruments used for stereoscopic plotting are one important limiting factor in DEM accuracy. Other factors are well known and usually expressed in terms of

contour accuracy. "Contour accuracy depends . . . also upon the nature of the terrain, the camera and its calibration, the quality of the photography, the density and quality of ground control, and the capability of the plotter operator" (Wolf, 1983:418).

Error in DEMs created photogrammetrically from aerial photographs has been defined the most comprehensively and by numerous sources (e.g., Wolf, 1983; Hakkarainen, Kilpela & Savolainen, 1982; Doyle, 1978). Torlegard, Ostman and Lindgren (1984) reported for the International Society of Photogrammetry and Remote Sensing (ISPRS) on a test that revealed the pattern of error in large-scale DEMs created photogrammetrically.

In the ISPRS test, the researchers requested DEMs from a variety of photogrammetric mapping firms. The participants were provided the air photos for six test areas and asked to create DEMs from them. In addition, the participants recorded information on the production process and were asked to assess the accuracy of the DEMs. DEMs created from larger scale photography was used as reference data to assess the test DEMs. The project leaders came to several conclusions. The experience of the operator played an important role in DEM quality. Almost all of the firms over-estimated the accuracy of their products, especially for a particularly rugged study area. Forested areas were not handled consistently, and were another area of generally poor quality.

The trend toward automation, as discussed above, has led to methods of extracting elevation information from digital images without the need for an operator to make the stereoscopic measurements. Automated methods are fast, but they create special problems with accuracy of DEMs. Problems associated with collecting data from areas of rugged

terrain, dense vegetation and featureless areas are common to all DEM production methods. These problems have been especially difficult to overcome with automated methods.

The major problems with automated methods have been known for decades. An early edition of the Manual of Photogrammetry (Amer. Society of Photogrammetry, 1966) noted that the performance of the automated systems were not equally predictable in a variety of terrains. This was because "[t]he machine does not recognize forms, search for shapes or memorize objects. Thus, when the automatic instrument is confronted with a situation where the two corresponding images differ considerably in appearance it can no longer function properly" (Amer. Society of Photogrammetry, 1966: 764). Steep terrain was one such instance. Further, the instruments tended to "get lost" when the correlation between the two images was not possible at some point. Recovery required an operator. Another problem was water (Carter, 1987). Water bodies reflect the sun and make the mechanical correlation impossible.

The Gestalt Photomapper (GPM-2) was one of the first DEM production systems that allowed automation of the production of DEMs (Kelly, McConnell & Mildenerger, 1977; Allam, 1978). It was used extensively by the USGS. The system was based on the principle that like-looking areas on two stereopair images could be identified by finding areas of image correlation. When the best correlation between the two images was found for a particular point, the elevation for that point was computed based on the parallax between the two images. An operator needed to be on hand to get the GPM-2 back on track when it became "lost" in the terrain. The GPM-2 was a significant step

forward in the automation of DEM production, but the early models often had obvious patterns associated with the patches used for the correlations (Carter, 1987; O'Callaghan & Mark, 1984).

Another problem associated with automated techniques is the production of false elevation values from the presence of trees, buildings, and other protrusions on the earth's surface. Automated techniques cannot detect whether an elevation value sits on the ground or on a tree top. A clearing in the forest would appear as a pit in the DEM. For some applications, such as visual terrain simulations, this effect may be desirable. In other cases, such as when the DEM is used for extraction of drainage networks, these errors need to be recognized and eliminated from the DEM during editing to produce more accurate DEMs (O'Callaghan & Mark, 1984; Hutchinson, 1989).

A fairly simple global digital filtering can eliminate false pits and systematic patterns in some instances (Allam, 1982; O'Callaghan and Mark, 1984, Stitt, 1990). More complex local filtering can correct some of the error in DEMs produced with automated correlation techniques. The filtering will also result in smoothing of the data, however, and this should be avoided to preserve topographic detail (Hannah, 1981). The effect of tree cover could also be reduced during DEM production through identification of forested areas and then subsequent subtraction of tree height from the estimated elevation.

Vincent (1987) described three problems and his solutions associated with automatic correlation. Featureless areas, such as bodies of water or ice, leave nothing for the correlators to work with. He has used nearest-neighbor interpolation to fill in featureless areas. Steep areas are distorted because of parallax effects. This problem can

be reduced by doing correlation searches over larger areas at one time. When search areas are too large, however, the automatic correlation systems tend to get lost. Vincent used a digital filter to remove unrealistic parallaxes, eliminating the need for an operator.

#### Error in SPOT Image Source DEMs

Several studies have focused on SPOT derived DEMs. The methods used to create the DEMs varied somewhat. In many cases, digital imagery was used to collect the elevation data. In earlier examples, a film product produced from a digital image provided the input data. Both manual and automated methods have been employed in the data collection process. Notably, the reported error and estimated map scale of the SPOT derived DEMs varied considerably among the studies.

Konecny et al. (1987) used SPOT image film products with photogrammetric instruments to develop a rigorous method to produce a DEM given the geometry of the SPOT image. Unlike aerial photography, for which all parts of an image are recorded simultaneously, SPOT imagery is collected line by line as the satellite orbits. The fact that the satellite and the earth are moving as the image is being collected makes it necessary to compensate for these additional variables. These variables are systematic, and they can be rectified with relatively little difficulty. Konecny et al. (1987) were able to create a DEM from this imagery with an elevation RMS error of 7.5 meters. They concluded that the SPOT imagery was sufficient to create topographic information at a scale of 1:25,000.

Rodriguez et al. (1988) examined the accuracy of SPOT DEMs using different image geometries and spectral modes. Like Konecny et al. (1987), they created DEMs

from photographic products using stereo plotters. They found that elevation errors averaged 7 meters. The effects of different base/height ratios on the accuracy of the DEMs were examined. The base is the distance between the satellite locations at the time when the images were obtained. This varies, while the height remains constant at about 832 km. A ratio of about 0.6 is recommended for stereoscopic SPOT images (SPOT image order form). Rodriguez *et al.* calculated a vertical accuracy of 3.5 meters for a B/H ratio of 1, and an accuracy of 7 meters was achieved for a B/H ratio of 0.5. The orientation of the imagery has a strong impact on the accuracy of the DEM. Guban and Dowman (1988) discussed the problem of image quality. Cloud cover on SPOT images affects the degree to which elevation values may be sampled. For some places, "cloud-free" conditions are impossible. They also noted that the process used to create the film product from the SPOT digital image impacted image quality. They examined the film products produced from digital imagery from several suppliers. The film products varied greatly in the degree to which they accurately replicated the original image. They also found that the experience of the operator played an important role in DEM quality. In particular, the operator needed experience with interpreting very small scale images. Guban and Dowman were rather more critical of the potential of SPOT derived DEMs than the previous two examples. They concluded that SPOT was suitable for mapping at 1:50,000 scale or smaller.

Ley (1988) used three different stereo plotting systems to extract elevation information from both digital and film SPOT images (depending on the system). One was a totally digital environment, one was a traditional analytical plotter that used a film

product, and the third was a hybrid. Ley found that areas of steep terrain and poor contrast had the lowest accuracy, and gentle terrain with high contrast, the highest. Even with optimal terrain and contrast, the base-height ratio of the two image limited the accuracy of measurements. On average, errors were 10 to 20 meters.

The error in SPOT derived DEMs documented in the above examples estimated average error between 3.5 and 20 meters. The number of different parameters that affected image and DEM quality provide a clue to the reasons for the differences. The question of operator experience is an important one, which should become less of a problem in production environments, but which will remain an important factor for in-house desktop workstations capable of stereoscopic data collection. The methods and expectations of data quality with SPOT DEM are still evolving. Expected error may vary greatly from one DEM to another.

#### Error in DEMs from Contour Interpolation

Several problems are associated with the use of interpolation techniques. The most accurate part of the DEM is closest to the contour lines. As with contour maps, the area between contours is assumed to change more or less predictably, but naturally, it does not. J. Carter (1987) found spikes and a "false butte" in a USGS contour interpolated DEM. The spikes were associated with DEM points that fell on a spot elevation. Carter also noted the difficulty in accurately digitizing areas where contours crowd together on the topographic map. This occurs frequently in areas of very steep terrain. Other problems

arise due to the mass and complexity of the data. It is difficult to develop computer programs that deal effectively with all possible terrain configurations.

Another artifact common to contour interpolated DEMs is banding that corresponds with the location of the original contour line. The pattern may be visible in a graphic display of the DEM or be visible as spikes in a histogram of the elevation values. It occurs when contour lines are widely spaced and many cells are assigned the same value as the original contour line. This effect has been noted with bicubic spline interpolation, which was used for the 1:250,000 equivalent DEM distributed by the USGS (Isaaks & Srivastava, 1989).

### Summary

In this chapter, I summarized the common typologies of error in DEMs. These are important for an understanding of the goals of research focused on DEM error. Next, two current topics of interest in DEM error research were considered. These were first, fractals and secondly, spatial autocorrelation. Each one of these topics, in the context of DEM accuracy could constitute a major research effort of its own. The questionable applicability of fractal theory to real terrain surfaces led to it being put aside for the present. Spatial autocorrelation is certainly related to the present research, and it proves to be an important factor in the research results that follow in later chapters.

The second half of this chapter was concerned with the methods of assessing error in DEMs. The methods reviewed here were subsequently applied in the assessments

described in Chapters VI and VII. Finally, previous research on DEM error from various methods was reviewed. The results from this dissertation research may be compared, to some extent, with other studies. An additional element in the current research, missing from most previous work in DEM accuracy is the assessment of the quality of a derivative product, the viewshed, and its relationship to the pattern of error in the original DEMs. The work in remote sensing related to error matrices and analyses of patterns of error in image classifications will be directly applicable when considering viewshed error.

## CHAPTER V DATA AND METHODS

### The Study Area

The DEMs used for the error assessments were all collected for the same area in Fort Knox, Kentucky. Fort Knox is located in North Central Kentucky, just south of Louisville, Kentucky (Figure 5-1). It is an area of karst topography, characterized by "an irregular terrain punctuated with many depressions, called sinkholes, or sinks" (Tarbuck and Lutgens, 1990:275).

The rolling hills, with some very steep slopes, are covered with dense forests interspersed with short grass and shrub-covered plains. The elevation above mean sea level ranges from 116 to 301 meters. This area is part of the physiographic region known as the interior low plateaus province (Thornbury, 1965).

The study area was chosen for two reasons. First, data availability was enhanced by intensive mapping of this region by the United States Army for a variety of projects. Second, the tree cover, the steep slopes and the presence of standing water make this fairly difficult terrain to map. The complexity of the terrain added to the usefulness of the DEM comparisons. The study area comprised about 120,200 acres. Some of the test DEMs were for only a portion of this area.



Figure 5-1  
Fort Knox, Kentucky

### The Geographic Information System

The GIS functions for this project were performed on a UNIX-based workstation from SUN Microsystems (Mountain View, California). The workstation was the model SUN4c, also known as an IPC. The machine was provided by Professor Grant Thrall in his research lab. The GIS software was the Geographic Resources Analysis Support System (GRASS). GRASS is a public domain software package developed by the U.S.

Army Construction Engineering Research Laboratory in cooperation with many federal agencies, universities and private organizations.

GRASS is particularly well-suited for raster analysis. It was designed originally for this type of analysis, and it includes a large suite of tools for manipulation of raster data (USACERL, 1991). Since all the DEMs in this project are in raster format, this functionality fulfilled project requirements. A statistical package supplemented the GIS. Data from the GIS were output as ASCII files and then read into the database for the statistical package.

### The Digital Elevation Models

Five digital elevation models were included in the assessments. One was a control model, the other four were test models. Two of the test models covered a much larger area than did the other two. These two were tested more extensively than were the others. Table 5-1 summarizes the characteristics of the models. Figure 5-2 shows their extent and relative locations within the study area. The models are each described below.

#### The Control Model

The DEM of the highest accuracy served as the control, or reference, model. It was used to represent true elevation values. Engineering accuracy standards dictate that check points used to check the accuracy of mapping are of "adequate accuracy" if the

check points are estimated to be of equal or greater accuracy than the map to be assessed (Merchant, 1983). This DEM was judged to meet that criteria, and the DEM was deemed adequate for the purpose of assessing the test models.

The use of an entire DEM for reference data rather than discrete points provided by a ground survey, was an important aspect of this project. The reference DEM allowed the entire range of values in the test DEMs to be assessed. It was this which provided a picture of the spatial pattern of error in the test models which would otherwise not have been apparent. To duplicate this with ground survey points would have been prohibitively expensive.

The control DEM was produced by the photogrammetric firm, Aerometric Engineering, in Sheboygan, Wisconsin. This firm was selected - on the basis of the quality of previous work and a competitive bidding process - to produce a DEM with a 10 meter horizontal resolution for Fort Knox, Kentucky. The DEM was produced for the entire 120,278 acre study area. The vertical precision of the elevation grid was in decimeters. The values were stored in the database as integers for this and all other raster maps. In order to preserve precision, the values in decimeters were multiplied by ten and then stored.

The DEM was created photogrammetrically by collecting mass points and critical elevation values from 1:24,000 scale photography, flown at 12,000 feet. An operator directed the spatial distribution and the quantity of the elevation sample points using a variant of progressive sampling. The aerial photography had been used for a previous mapping project for mapping at a scale of  $1" = 400'$ .

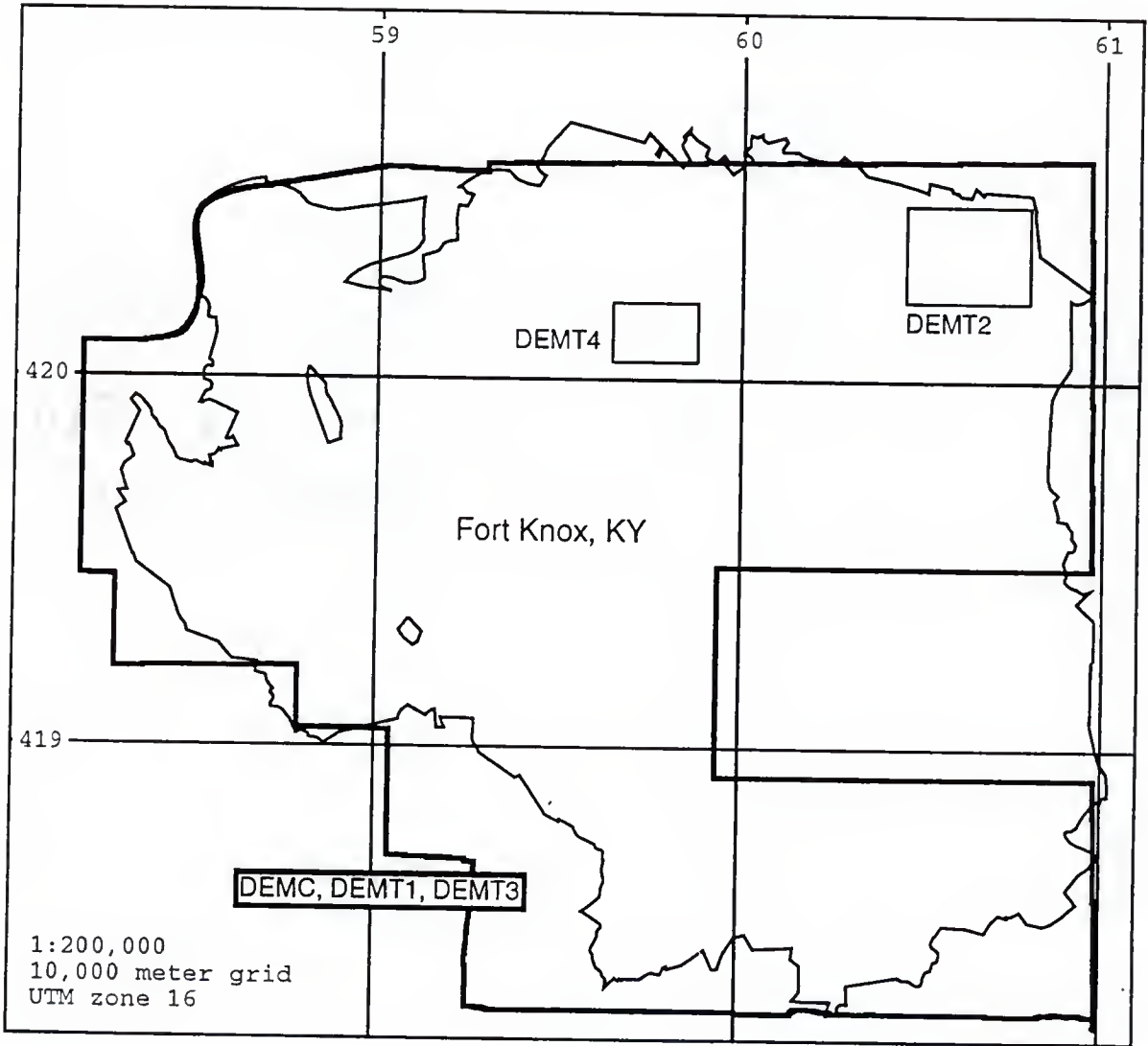


Figure 5-2  
The Study Area

Table 5-1  
An Overview of the DEMs

| DEM    | Type/Source                                                                                | Hor. Res. | Acres   |
|--------|--------------------------------------------------------------------------------------------|-----------|---------|
| DEMC   | Traditional photogrammetry<br>1:24,000 air photos                                          | 10 m      | 120,278 |
| DEMT1  | Automated method from digital<br>SPOT panchromatic imagery                                 | 10 m      | 120,278 |
| DEMT2  | Automated method from scanned<br>1:80,000 air photos (NHAP)                                | 3 m       | 2,222   |
| DEMT3  | USGS 7.5' DEMs from NHAP photos<br>GPM-2 and manual profiling                              | 30 m      | 120,278 |
| DEMT3a | USGS 7.5' DEM - Fort Knox quad<br>NHAP w/GPM-2                                             | 30 m      | 37,490  |
| DEMT3b | USGS 7.5' DEM - Rock Haven quad<br>NHAP w/manual profiling                                 | 30 m      | 15,193  |
| DEMT4  | Contour interpolated - inverse<br>distance weighted from 1:24,000<br>digital contour lines | 10 m      | 935     |

#### The SPOT-Derived Test Model

The first test DEM (DEMT1, Table 5-1) was derived from panchromatic imagery from the French satellite - Système Pour l'Observation de la Terre (SPOT). Although acquisition of the two scenes was requested for Spring, 1990, cloud cover prevented acquisition of the second scene during that season. The second scene was acquired in Spring, 1991. The one year difference in the dates of these scenes was not ideal, but this problem has been typical of SPOT-derived DEMs. The test data collected were not

intended to be representative rather than ideal. They were meant to represent the data available to a GIS user for intermediate-scale mapping.

The SPOT-derived DEM was purchased through the SPOT Image Corporation (Reston, Virginia). The creation of the DEM was subcontracted to a value-added firm, but the quality assurance came from SPOT. The DEM had a horizontal resolution of 10 meters and a vertical precision of 1 meter. The elevation data were collected using an automated image correlation process from the two digital images. The control points used for image rectification came from USGS 1:24,000 quad sheets. The overlap area of the two images was 2647 square kilometers (654,050 acres), about 75% of the size of the typical, 60 km by 60 km, SPOT scene. The 120,278 acres of the study region was cut out of this larger DEM and used for the test.

#### The NHAP Test Model

The second test model (DEMT2, Table 5-1) was derived from high altitude aerial photography from the United States National High Altitude Aerial Photography program (NHAP, now called NAPP). Geospectra Corporation (Ann Arbor, Michigan) digitally scanned the 1:80,000 scale black and white photographs at a 25 micrometer spot size. This resulted in a pixel size of 2 meters (ground units), which were subsequently resampled (by Geospectra) to 3 meters. The elevation values were calculated from this very dense grid using proprietary software called ATOM (Vincent, Pleitner, and Oshel, 1984). The resultant DEM comprised 2222 acres. Horizontal resolution was 3 meters and

vertical precision was 1 meter. Ground control for geo-processing came from 1:24,000 scale quad maps.

### The USGS Test Models

The third test DEM (DEMT3 in Table 5-1) was a set of models purchased from the U.S. Geological Survey. These were in the 30 meter (horizontal resolution) series, corresponding with 1:24,000 scale map coverages. Of the five USGS DEMs included in the study area, one was produced using manual profiling with NHAP photography, and the other four were products of NHAP and the Gestalt Photomapper (GPM-2). The elevation values of these DEMs were in meters above local mean sea level. The five quads, or parts of quads were trimmed to correspond with the 120,278 acres of DEMC.

Two different production methods were represented in the five USGS DEMS. Four of the DEMs were produced by the GPM-2. One of them was produced through manual profiling. All were from NHAP photography. The four GPM-2 DEMs were produced in the late 1980's. No date was provided with the manual profiling DEM. All of the USGS DEMs had the Level 1 error classification. The header file included with the DEMs indicated that three of the GPM-2 DEMs had relative accuracy of 7 or 6 meters RMSE. The fourth GPM-2 DEM did not include accuracy information in the header file. The manual profiling DEM header file reported an accuracy of 4 meters.

### The Contour Interpolated DEM

The fourth test DEM (DEMT4 in Table 5-1) was interpolated from digital contour lines digitized manually from a 1:24,000 scale USGS map. The contours were at a 20

foot interval with supplemental 10 foot contours. The contour lines were digitized as vectors and then rasterized to a 10 meter resolution grid. The elevation values were stored in decimeters. The area of DEMENT4 was about 1000 acres.

An inverse distance weighted interpolation program was used to fill in the final DEM from the rasterized contour lines (Isaaks and Srivastava, 1989; USACERL, 1991). In this algorithm, the z-values are calculated to give greater weight to closer known points than to those that are more distant. For the interpolation of this DEM, the 12 closest original elevation points determined the interpolated values of the output map.

### Data Processing

#### Datum and Coordinate System

The change in datums with the "new" 1983 North American Datum was not an issue in this project, because the North American Datum of 1927 was the reference datum for the horizontal locations in all of the DEMs. All elevations were calculated in terms of their distance in meters above average mean sea level as determined by the National Geodetic Vertical Datum of 1929.

The DEMs were all projected in the Universal Transverse Mercator (UTM) projection. The x and y coordinates were all determined by the UTM grid system for zone 16. All of the DEMs were brought into the data base with the GRASS software. The DEMs were all stored in their original forms, but they required some resampling

prior to the assessments. This was necessary because the DEMs were stored with different geographic extents and resolutions.

### Resampling

GRASS uses the concept of a "region" in which data are stored or analyses are performed. Each GRASS raster file includes a header with information on the geographic extent (north, south, east and west boundaries) and spatial resolution of the map. In the GRASS database, each individual DEM has its own region defined in its header file. When two DEMs with different resolutions or extent are used in the same analysis, resampling of data from at least one DEM was required. For the first part of the research, in which differences and ratios were calculated, the test DEM provided the region information. The control was resampled to match the test using the default resampling algorithm, which was nearest-neighbor resampling.

The comparison of values between the control and test models occurred at the center point of each corresponding grid cell of the two models. This was not as precise as a point by point comparison using control points identified by x, y and z coordinate values. The large number of cells compared, however, was an important aspect of this research. The comparison of whole surfaces rather than discrete points or profiles gave a look at the "big picture." Li (1990: 7), for example was particularly aware of the need ". . . to extend [DEM accuracy] analyses to a complete surface." Although grid cells are, theoretically, discrete points; they are conceptually similar to a surface.

For the second part of the research, in which the viewsheds from the DEMs were compared, a different logic was used regarding resampling. For this part, all of the DEMs that were not stored at a ten meter resolution were resampled to match the control DEM. All of the viewshed calculations and the measurements of slope, tree cover and the selection of viewpoints were performed for a set of regions defined by the control DEM. The sheer volume of data processing required for these comparisons made this simplification necessary.

### Viewshed Calculations

Each of the DEMs was used to derive a set of viewsheds. GRASS was used for this task. The GRASS viewshed algorithm identifies all of the grid cells that are visible from a specified point. The observation point provides the location of the viewer in three dimensions, both the x-y location and the height above the ground of the observer. For this analysis, the height of the observation was set at 1.75 meters above the elevation found at the point at which the observation was made.

In order to reduce the number of data values around each observation point, a limit of 500 meters from the observation point was set, with the viewshed being calculated only up to that limit, in all directions from the observation point. The location of the observation points were chosen using a random point generator available in the GRASS GIS. This type of random number selection is actually "pseudo-random" since the same series of numbers is used each time the program runs. It was deemed adequate for the present purpose.

The random selection of points was performed three times. Each of the two smaller areas, covered by DEMT2 and DEMT4, were treated as individual subregions for the viewshed assessment. A set of 30 observation points were selected at random in each of the subregions. A third set of 61 observation points were selected for the entire study area as described below.

Viewsheds were calculated at 61 random observation points spread around the study area. The points were selected using a stratified random selection strategy. The USGS 7.5' quad coverage areas were used as the stratum. The number of points selected from each quad area was determined by the area of the quad that was within the study area. The number of sampled points was proportional to the percentage of the total study area represented by a particular quad or partial quad.

After the number of observation points for each quad was determined, a simple random sampling was performed from all the possible locations within that quad. Two additional constraints were placed on the location of the observation points. First, the 500 meter buffer area around the point could not overlap with the area of another point. Second, the 500 meter buffer area was not allowed to overlap into an adjacent quad. Points that did not meet these criteria were discarded, and new points were selected to replace them.

#### Other Variables in the Analyses

In addition to the viewshed and the DEM accuracy variables, a number of other variables served as explanatory variables. The measurements and methods used to create those independent variables are described below.

### Slope Steepness

The steepness of slope incline plays an important part in explaining the variation in the accuracy of DEMs. For this variable, the control DEM was used. A GRASS program calculates slope in degrees. This was reclassified into percent rise, which is the tangent of the slope value in degrees. Each pixel in the slope map thus contained the value of the percent incline of that pixel.

### Tree Cover

Tree cover data was classified from SPOT 20 meter multispectral imagery. Cloud cover was a problem, an ortho-corrected image from 10 meter SPOT imagery provided data on the areas covered by clouds. The image classification was performed using GRASS classification programs. For the 61 viewshed areas used in the final analysis, each 500 meter radius circle was examined individually to improve the tree cover classification for those areas. The major source for this was the SPOT panchromatic image.

### Height

Several height variables were used in this analysis. For the DEM accuracy assessments, height was found to be a significant factor in explaining the variation in accuracy. When height classes were used to aid in this assessment, the classes were based on the true height of the area, as determined by the control DEM. The height of the observation point was also a factor in terms of viewshed accuracy. The average height

of each viewshed area was a third height variable. These variables were, once again, measured from the control DEM.

### Diversity Measure

The measure of diversity has been used in remote sensing. The measure used in this research was based on a GRASS filtering program. The program allowed the calculation of the number of cells of different values in an n-cell neighborhood. This was used to measure the diversity of the EVTV ratio values of the DEMs. A nine cell neighborhood was used. The neighborhood was passed across the original EVTV maps and a new map was created with values ranging from 1, meaning all values in the corresponding neighborhood were the same, to 9, meaning that all values in the neighborhood were different.

The diversity measure was used as a proxy for an estimate of spatial autocorrelation. The spatial autocorrelation measure, Moran's I, was used to measure this dimension of the ratio maps. It was found that with a 25 cell neighborhood, the average I value of the EVTV ratio in the 61 viewshed areas was over .9 in all cases. Basically, the error was highly autocorrelated. The difference between .91 and .93 in a measure that is not particularly sensitive, was not deemed useful. The diversity measure was used instead.

### Path Analysis

The conceptual model that was developed at the end of this research was guided by the concepts of path analysis, as defined by Loehlin (1987). This method has been

used by social scientists to help to bring order to a large number of inter-related variables. Path diagrams are an important tool for this effort. The path diagram uses straight lines with arrows between variable names to represent a causal relationship between two variables. Curved lines with arrows represent a correlation between two variables (Figures 7-5 and 7-6).

The variables may be either observed or latent. Latent variables are those which may not be fully measured, but instead are represented by a number of observable variables. Latent variables are often called factors, and are depicted as ovals or circles in the path diagram. In this analysis, DEM error was considered a latent variable, as measured by RMSRE, diversity and slope. Factor analysis is often used to determine which observable variables are related and may be measuring a latent variable.

Observed variables are depicted as squares or rectangles. Variables in a path diagram are also defined as either exogenous or endogenous. The exogenous variables are the independent variables. In path analysis, other variables within the path diagram do not explain exogenous variables. This means that causal arrows may leave them, but not go toward them. The endogenous variables are those which are explained by the variables within the path diagram. These are also known as downstream variables. Endogenous variables have causal arrows that point toward them.

This method of organizing the variables was very helpful for this research. It allowed the complexity of the data to be more fully exploited in a manner that would have been easily overlooked using a series of multiple regression models. The solution to the problem was found to be a two level process. First, there was the question of the

factors that affected DEM quality. Then, there was the question of how these factors and DEM quality affected the viewshed outcomes. These questions could not be handled adequately with a straight regression analysis. The final assignment of weights to the paths, which is the final goal of path analysis, was not performed for this research. This task was left for a future effort.

In this chapter, I provided details of the data collection, processing and analysis used in the research. This chapter provided basic background information on the Fort Knox study area. I introduced the GRASS GIS and the statistical software for the project. The control model and each of the test DEMs were described in some depth. The sampling of the observations points for the viewsheds was a key point in the methodology of the research. Finally, the path diagram techniques used in Chapter VII were explained and justified.

## CHAPTER VI

### ASSESSMENT OF THE DEM ERROR MAGNITUDE AND PATTERN

This chapter summarizes the results of several descriptive assessments of the test DEMs. Shaded relief renditions of the DEMs were first evaluated visually, with each test model being compared with the control model as well as with the other test models. The second assessment involved a calculation and comparison of the root mean square error of each of the test models, using the control model as a reference. The difference maps created for the calculation of the RMSE provided a further means to compare and contrast the test models.

Limits in the use of differences, which can be negative numbers, led to the adoption of a ratio of the estimated value to the true value as a third means to evaluate the test DEMS. The spatial pattern of the error is visible in maps of the ratios. Finally, the spatial distribution of slope steepness, elevation height, water and tree cover were compared to the differences in the ratio measures. To complete this section, the diversity of error ratio values were calculated and compared to error magnitude values.

### Visual Assessment

Shaded relief renditions for each of the test DEMs and for the control DEM are illustrated in Figures 6-1 through 6-6. Each map was printed at 1:24,000, thus creating comparable views of each one. These figures were used for the visual assessment that is described in this section. The test DEMs were compared with the control DEM in terms of level of detail evidence of artifacts related to interpolation or the data collection process. Interpolation artifacts are often visible in the shaded relief map, though they are not apparent in the map of elevation (Wood & Fisher, 1993).

#### DEMC -- The Control Model

The shaded relief rendition of the control DEM (Figure 6-1 and Figure 6-5) illustrates graphically the potential of a highly detailed DEM. The topographic features are clearly defined and there is little visual evidence of features that do not appear to be part of the natural surface. These two figures will be used to compare and contrast with the other figures.

#### DEMT1 -- The SPOT Model

Figure 6-2 shows the shaded relief produced from the SPOT DEM (DEMT1). This is the same area as shown in Figure 6-1 for the control DEM. The most obvious feature of DEMT1 is its lack of detail. Though the model was produced at a resolution of 10 meters -- the same resolution as the control DEM -- the 10 meter control model is clearly of a higher level of detail. A user who assumed that all 10 meter DEMs could be used interchangeably may be disappointed by the information content of DEMT1.



Figure 6-1  
DEMC Shaded Relief



Figure 6-2  
DEMT1 Shaded Relief

### DEMT2 -- The High Density Model

Figure 6-3 is from DEMT2, the high density DEM produced with automated correlation and NHAP photography. This DEM has a horizontal resolution of 3 meters. The area depicted in this figure is upper three-fifths of the area shown in Figure 6-1. DEMT2 provides more detail than DEMT1. The areas with high relief differences are especially well rendered. The flat areas, however, are muddled by an indistinct salt and pepper pattern. The irregular flat area that appears about half way up the east side of the DEM is a lake.

### DEMT3 - The USGS Models

The shaded relief from DEMT3 is found in Figure 6-4. The detail in this depiction is once again considerably less than in Figure 6-1. The 30 meter cells of the USGS DEM are more clearly apparent than are the cells in the other test models, creating a patchwork quilt pattern in the southeast quadrant of the map. At 30 meters, this DEM had the lowest resolution of all of the test models. The hilly area in the north and west of this area are depicted more realistically by DEMT2 (Figure 6-3) than by this DEM. The hilly area is easily perceived as hills, though they are not very distinct in the northwest corner of the area. DEMT3 performs better in terms of overall information content, than does DEMT1. The stream that flows through the southeast part of this region is visible in DEMT3, while it was only vaguely visible in DEMT2 and absent in DEMT1.

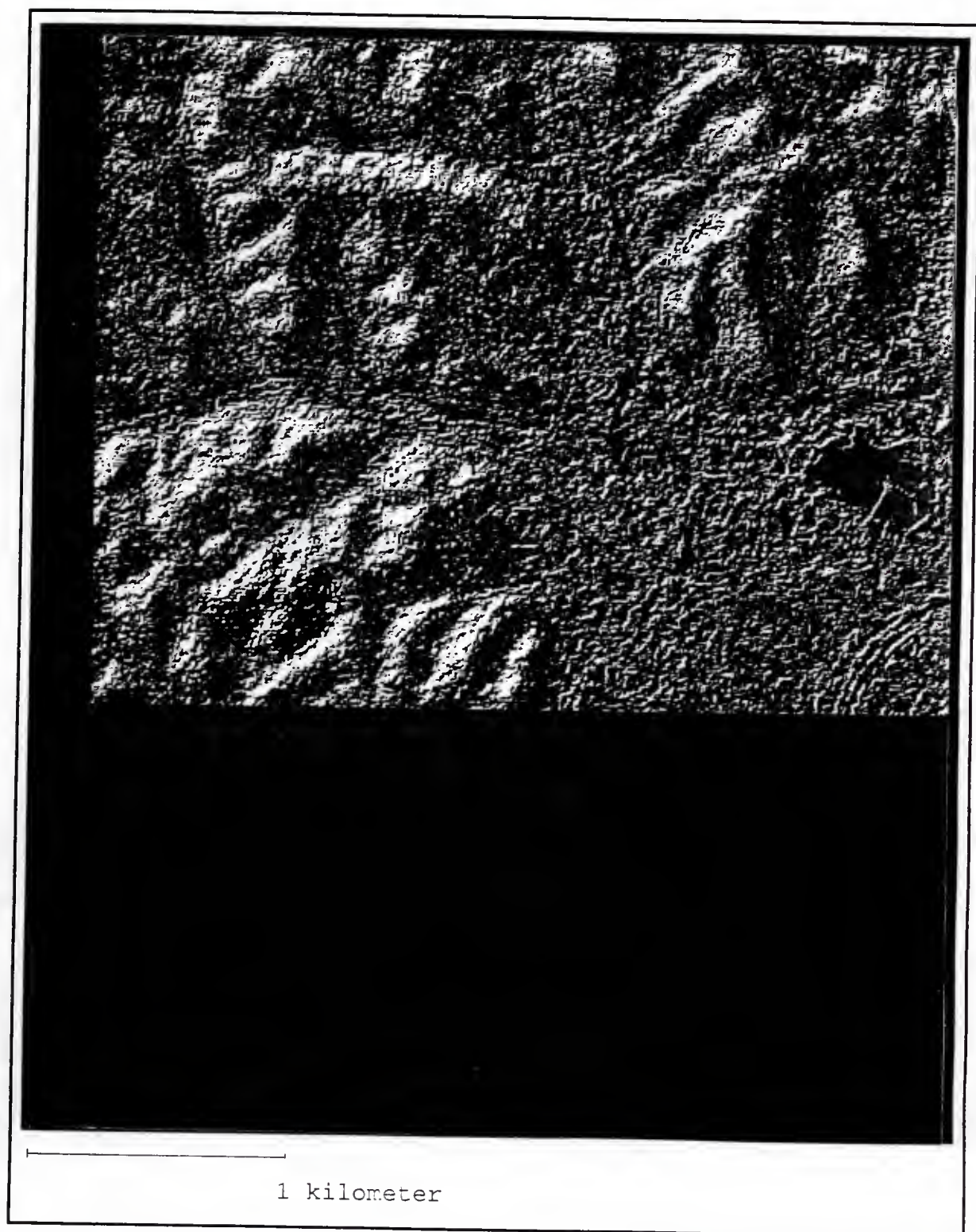


Figure 6-3  
DEMT2 Shaded Relief



Figure 6-4  
DEMT3 Shaded Relief

### DEMT4 -- The Contour Interpolated Model

Figure 6-5 is another view of the control DEM, and Figure 6-6 depicts DEMT4, the contour interpolated DEM. The scale is 1:24,000 for each, and the two figures are for the same area. The detail of DEMT4, which was stored at a ten meter horizontal resolution, compares favorably with DEMC. The terracing that is present in the flatter areas is typical of an inverse distance weighted interpolation. DEMT4 missed the detail of the lower area in the western part of DEM, because this detail was not apparent in the original contours. In order to portray the missing detail, the original input data would need to be made more dense. The interpolation was not necessarily at fault. In spite of its weaknesses, DEMT4 provides the best shaded relief rendition of the four test models.

### Summary of the Visual Assessment

The detail of the four test DEMs was markedly different among these models. None of the tests has as much detail as the control DEM. DEMT4, the contour interpolated DEM, was the most detailed of the test models, DEMT2 and DEMT3 were similar in content, and DEMT1 was, by far, the least detailed. From this simple comparison, it is clear that the horizontal resolution of a DEM is not necessarily indicative of its information content. Judging a DEM by its horizontal resolution would be similar to judging the content of a book by the number of pages it contained. The amount of information contained in the data source and the way in which the information was processed affected the information available. For the DEMs examined in this research, the horizontal resolution and the information content of the grid DEM are not consistently correlated.

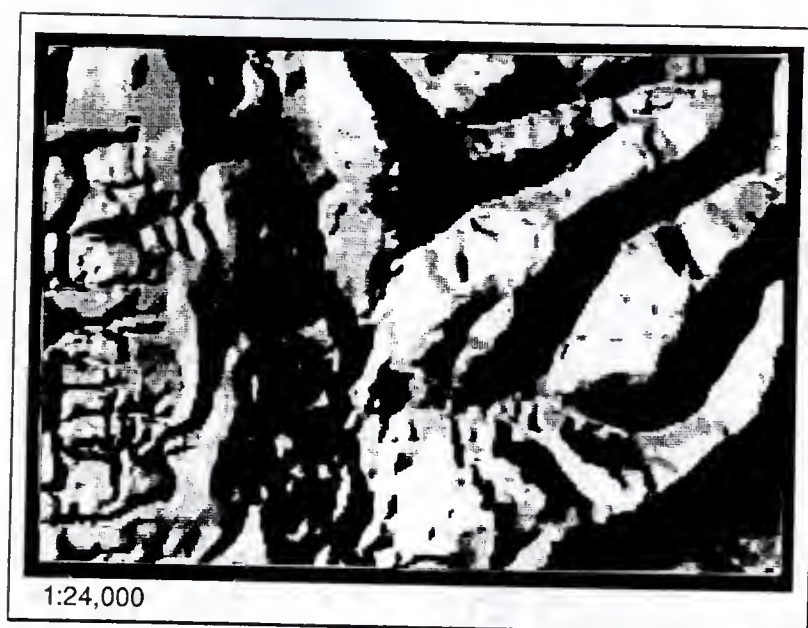


Figure 6-5  
DEMC Shaded Relief



Figure 6-6  
DMT4 Shaded Relief

### Root Mean Square Error and Differences

The second assessment of the test DEMs was a calculation of the root mean square error (RMSE) of each test model, using the control DEM as a reference. Chapter IV defines the RMSE. The difference maps required for the RMSE calculation are the values that are the result of the control map values minus the corresponding test map values. The summary statistics of the calculations are in Table 6-1. The RMSE of 17.02 meters for DEMENT1 was the largest of the RMS errors among the four test models. The lowest RMSE, of 3.75 meters was calculated for DEMENT4. DEMENT3 had the second highest RMSE value, at 9.10 meters. DEMENT3 is a composite of several USGS DEMs patched together. The five parts included in the assessment were created by two different production methods. The two methods used to create the several parts of DEMENT3 resulted in different magnitudes of error. The manual profiling method (DEMENT3b), used in one 7 1/2' quad area, had an RMS error of only 5.71 meters. The balance of DEMENT3, called here, DEMENT3a, was created with the Gestalt Photomapper (GPM-2). DEMENT3a had an RMSE of 9.44 meters. The final DEM, DEMENT2, had an RMS error of 7.26 meters, placing it between the two USGS DEM methods in terms of accuracy, but not as accurate as DEMENT4.

The difference maps for each of the test models provided another look at the error in the test models. The difference maps were created by subtracting the z values in the test models from the z values in the control model. Table 6-1 lists the range, the mean and the standard deviation of the difference maps. A negative value occurred when the

test model value was greater than the corresponding control value. A positive difference value indicates that the control model value was greater than the test model.

| Table 6-1<br>RMSE and Differences for Test DEMs |                    |             |        |       |
|-------------------------------------------------|--------------------|-------------|--------|-------|
| DEM                                             | RMSE               | Range       | Mean   | s     |
| DEMT1                                           | 17.02 <sup>a</sup> | -262 -- 159 | -14.06 | 10.70 |
| DEMT2                                           | 7.26               | -49 -- 41   | -2.38  | 6.96  |
| DEMT3                                           | 9.10               | -75 -- 109  | -6.15  | 6.62  |
| DEMT3a                                          | 9.44               | -75 -- 109  | -6.92  | 6.43  |
| DEMT3b                                          | 5.71               | -45 -- 36   | -1.92  | 5.38  |
| DEMT4                                           | 3.75               | -33 -- 15   | -0.67  | 3.78  |

a. All values are in meters.

The range of error in the difference maps was largest for DEMT1, as would be expected considering that the RMSE for the SPOT derived model was correspondingly high. The lower limit of the range was -262 meters. For DEMT1, then, there is possibility of an error more than 200 meters greater than the expected value. An error this large points to the possibility that blunders have remained in the final DEM. The area in error is quite small. Only 70 ten meter cells (about 1.7 acres of 147,000 acre region) had a difference of more than 100 meters, either more or less than the control model. These errors indicate a possible quality control problem during the production of DEMT1.

The range of error in the other test DEMs parallels the differences in RMSE for the models. The larger the RMSE, the larger the range of error. DEMENT2 and DEMENT3 are not clearly different from each other, though. The range of error for DEMENT2 was less than DEMENT3, DEMENT2 has a larger standard deviation than does DEMENT3. This indicates that DEMENT3 has some differences of greater magnitude than DEMENT2, but most differences are well-contained within a relatively narrow range.

All of the mean differences for the test DEMs were negative, throwing some doubt on the absolute accuracy of the control DEM. While it is possible that this occurred by chance, it does not seem likely that the  $z$  values of all the test models would be consistently higher than the control, unless the control model was systematically too low. A set of 19 independent ground control points (GCPs) was available to check the accuracy of the control model. While this was a small number, they were all that could be acquired without additional funding, which was not available.

The differences between the independent GCPs and the control model are listed in Table 6-2. At twelve of the nineteen sites, the control model was lower than the GCP. The average error was .545. A positive difference indicates that the lower than expected values slightly outweighed the higher than expected values. The largest differences between the GCP and control model were found at sites 11 and 16, with differences of 3.08 and 4.31 meters respectively. The RMSE for the control model compared to the GCPs was 1.36 meters.

The control model was not intended to represent absolute truth. Rather, it was a control of greater accuracy than the test models. Based on the available independent

check points, the control model was slightly low, overall, compared to ground truth. The RMSE of 1.36 m. for the control model was less than any of the RMS errors for any of the test models compared to the GCPs. This indicated that the control was of higher accuracy than any of the test models. The RMSE values calculated using the control as a reference are not absolute, however, so comparisons with other research in which DEMs are evaluated against GCPs should be done with the 1.36 m difference in mind.

### EVTV Ratios

The RMSE values were calculated for the test models in order to provide a link with the majority of the research literature on accuracy in DEMs. For this project, however, the negative numbers that were in the difference maps were cumbersome in later quantitative analyses. One solution could have been to use absolute values of the differences, but useful information would have been lost, since values above and below the true values would be treated the same. For these reasons, a ratio of the estimated to the true value was calculated for the test models and was used in all subsequent analyses.

The ratio is called the EVTV ratio. As outlined in Chapter IV, the mean ratio may be expressed as a percentage, called the mean ratio. Also described in Chapter IV was the Root Mean Square Ratio Error. The Root Mean Square Ratio Error (RMSRE), based on the EVTV ratio, provides a measure of the EVTV ratios analogous to the RMS error, which is based on differences. The RMSRE is expressed as a percentage.

Table 6-2  
GCPs and DEMC Differences

| Site | GCP                 | DEMC  | Diff  |
|------|---------------------|-------|-------|
| 1    | 225.81 <sup>a</sup> | 225.6 | 0.21  |
| 2    | 222.85              | 222.2 | 0.65  |
| 3    | 136.99              | 137.2 | -0.21 |
| 4    | 138.60              | 138.6 | 0     |
| 5    | 241.42              | 241.5 | -0.08 |
| 6    | 222.75              | 221.5 | 1.25  |
| 7    | 253.16              | 252.0 | 1.16  |
| 8    | 135.55              | 136.3 | -0.75 |
| 9    | 205.59              | 205.3 | 0.29  |
| 10   | 225.08              | 224.8 | 0.28  |
| 11   | 244.78              | 241.7 | 3.08  |
| 12   | 214.70              | 214.0 | 0.7   |
| 13   | 220.82              | 221.6 | -0.78 |
| 14   | 128.41              | 128.5 | -0.09 |
| 15   | 127.19              | 126.3 | 0.89  |
| 16   | 138.51              | 134.2 | 4.31  |
| 17   | 133.58              | 134.1 | -0.52 |
| 18   | 138.44              | 137.8 | 0.64  |
| 19   | 134.62              | 135.3 | -0.68 |

a. All values are in meters.

The RMSRE has a direct relationship with the RMSE. Table 6-3 summarizes the statistics on the EVTV ratio for the test models. An EVTV value of 100 occurs for an individual cell when the control and test models are identical for the cell. A mean EVTV value of 100 indicates that, on average, the ratios for the test model are 100. The picture

from the RMSRE is the same as described above for the RMSE. DEMENT1 exhibits the greatest difference from the control DEM, with an RMSRE of 10.37. The lowest RMSRE value is for DEMENT4, at 2.42.

| Table 6-3<br>EVTV Ratios for the Test DEMs |                     |                  |              |                    |              |
|--------------------------------------------|---------------------|------------------|--------------|--------------------|--------------|
| DEM                                        | Mean                | Range of<br>EVTV | s of<br>EVTV | RMSE               | <b>RMSRE</b> |
| DEMT1                                      | 107.47 <sup>a</sup> | 12 - 248         | 6.77         | 17.02 <sup>b</sup> | 10.37        |
| DEMT2                                      | 102.08              | 80 - 138         | 4.58         | 7.26               | 5.03         |
| DEMT3                                      | 103.94              | 49 - 145         | 4.0          | 9.10               | 5.46         |
| DEMT4                                      | 100.61              | 92 - 124         | 2.34         | 3.75               | 2.42         |

<sup>a</sup> mean values are a percentage  
<sup>b</sup> RMSE values are in meters

### Spatial Patterns of EVTV Ratios

The error revealed by the EVTV ratios exhibits distinct spatial patterns. Figure 6-7 illustrates this for the SPOT DEM (DEMT1). In DEMENT1, the pattern bears a strong resemblance to the terrain. Lower areas near to stream drainage seem to be generally higher than the reference value and higher areas are lower than the reference value. This represents a collapsing of values, taking away highs and lows, and may be a result of smoothing.

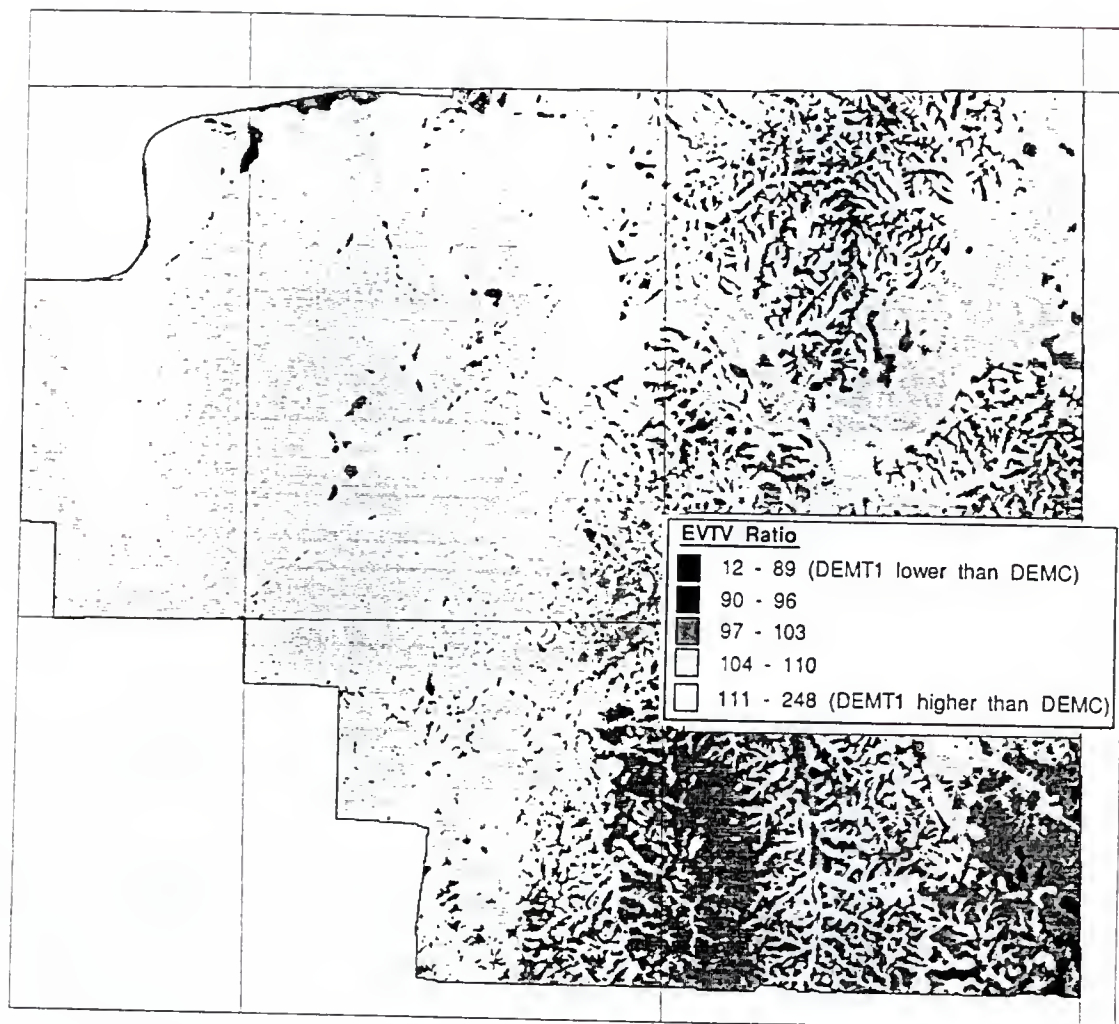
A trend across the SPOT DEM is also apparent. Starting from the northwest corner and proceeding to the southeast, the error goes from being a result of values too high to too low. This pattern does not seem to be related to the terrain, but rather, may

have to do with the characteristics of the georeferencing of the satellite images used to produce the DEM.

Figure 6-8 is the same area as Figure 6-7, showing the EVTV ratio error for DGMT3, the USGS DEM. The two different production methods used for the USGS quads are apparent in this figure. The small rectangular patches, most visible in the center two quads, are typical of the GPM-2. The pattern is less visible in two eastern quads, also produced with GPM-2. The error of being lower than the reference is less pronounced in the two central quads than in the eastern ones.

The demarcation along the quad lines in Figure 6-8, separating the central from the east quads indicates that the two eastern quads have less area of the middle category - where the test values are about the same as the references values - than the others. The two superior, GPM center quads were both produced in 1990, the eastern GPM quads were produced in 1987. The more recent quads are of better quality in terms of quantitative error, but they still have more of problem with the patches appearing than the older ones do.

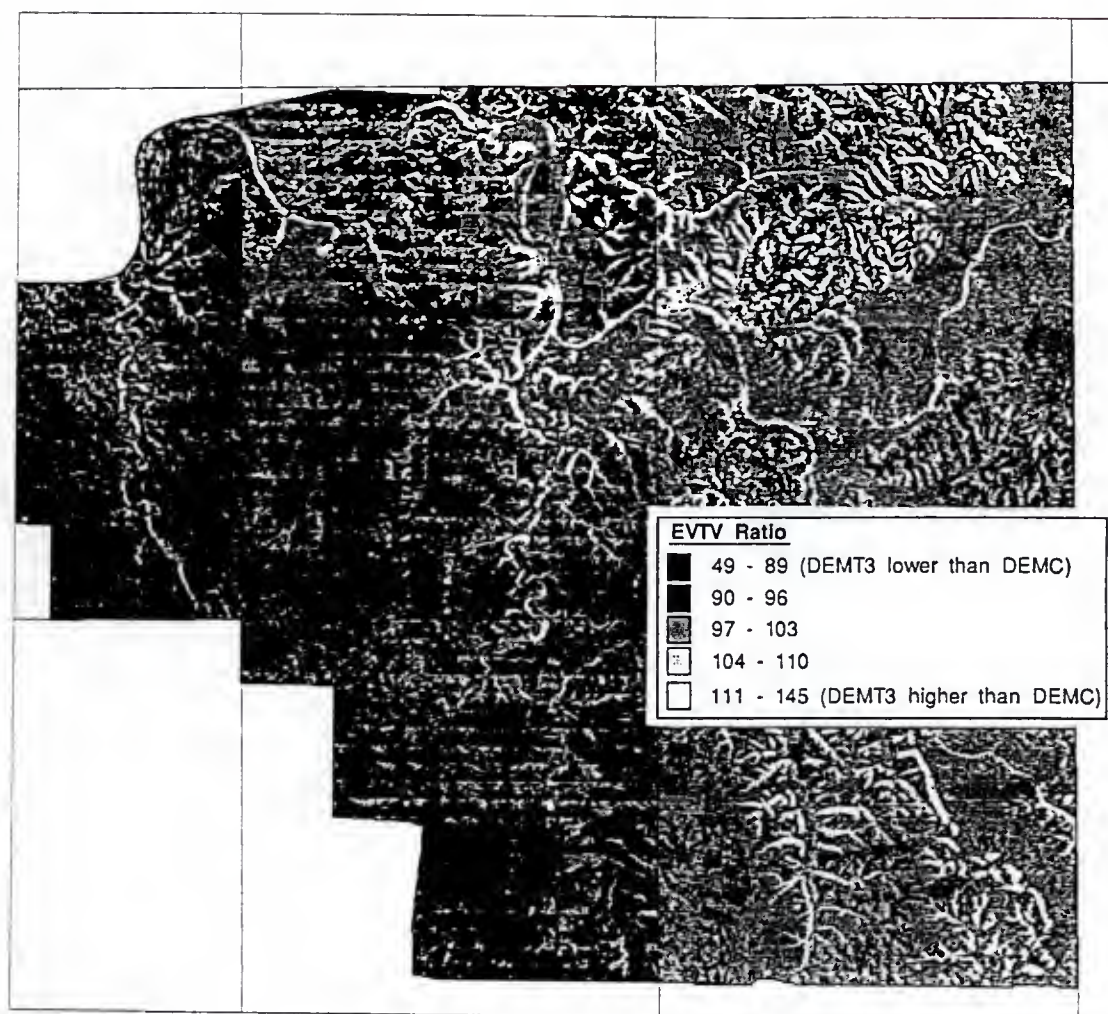
The western most quad was produced by manual profiling. It is free of GPM patches. In most of its area, the DEM has a ratio of around 100. The creek that runs through this quad has very steep sloped banks, and the area with the most error is almost all near the creek. There, the DGMT3 values were generally higher than the reference data. This quad is also free of the distinct linear pattern sometimes associated with manual profiling.



Scale is 1:200,000

The grid lines mark the boundaries of USGS 7.5' quads.

Figure 6-7  
DENT1 EVTV Ratios



Scale is 1:200,000

The grid lines mark the boundaries of USGS 7.5' quads.

Figure 6-8  
DEMT3 EVTV Ratios

The EVTV ratio of DGMT2, the high density, automated correlation DEM, is shown in Figure 6-9. A comparison with Figure 6-3, which shows the shaded relief for the same area and DEM, reveals that the lake and the river channel in the southeast corner posed a problem for this DEM, with the result being values that were higher than the reference values. The pattern of the rest of the area is somewhat related to the pattern of terrain, but not as markedly as DGMT1 and DGMT3. The main pattern of the error is a heterogeneous blend of ratios of different magnitudes reminiscent of the salt and pepper pattern of the shaded relief.

Figure 6-10 shows the pattern of the EVTV ratio for DGMT4, the contour interpolated DEM. The ratio for most of the area is close to 100. The patches of error are made of several well-defined areas, which are between contour lines. The areas farther from contour lines have a greater magnitude of error than those closer to the original contour lines.

In addition to artifacts related to data collection methods, the literature on DEM error suggests that error in DEMs varies with slope steepness, tree cover, and presence of water. In addition, it is expected that error that is in a random, scattered pattern will be of greater range than the systematic error, which will be in a spatially contiguous pattern. Finally, the visual assessments suggested that in some cases, there may be a relationship between the height of an observation and the magnitude of error at that location. The test DEMs were each examined to determine how the error in the DEMs varied with each of these factors. Table 6-4 summarizes the findings.

For the slope evaluation, the entire study area was divided into seven classes, based on slope steepness as measured by the reference DEM, DEMC. The root mean square EVTV error (RMSRE) for each of the seven classes was computed for each of the four test models. Based on the information in Table 6-4, two of the test models were most affected by slope steepness, though in opposite ways. DEMENT2 had a greater magnitude of error in flatter places. DEMENT3 behaved more like expected, and had more error in steeper places. DEMENT1 and DEMENT4 both had increased error with increased slope steepness. DEMENT1 also had a slightly higher RMSRE in the two lowest slope classes, and was lowest at the third class, before steadily increasing in magnitude of error as slope steepness increased.

Water bodies affected RMSRE magnitude. All of the test models had greater error in places with water than in places without water. DEMENT1, DEMENT3 and DEMENT4 were most affected with error almost two times higher in areas with water than in areas without. The presence of water played an important role in the error problems in the test DEMs, but the area involved was relatively small.

Tree cover resulted in higher error ratios for DEMENT1 and DEMENT3. For DEMENT2, the tree covered areas actually had a smaller RMSRE than the area without trees. The ratios for DEMENT4, whose source data was a 1:24,000 scale map, were not apparently affected by the tree cover as measured for this assessment.

The final assessment of the test DEMs involved a calculation of the error that was either more grouped or more scattered and apparently random. The diversity measure was described in Chapter 5. Table 6-5 shows the results from the calculations.

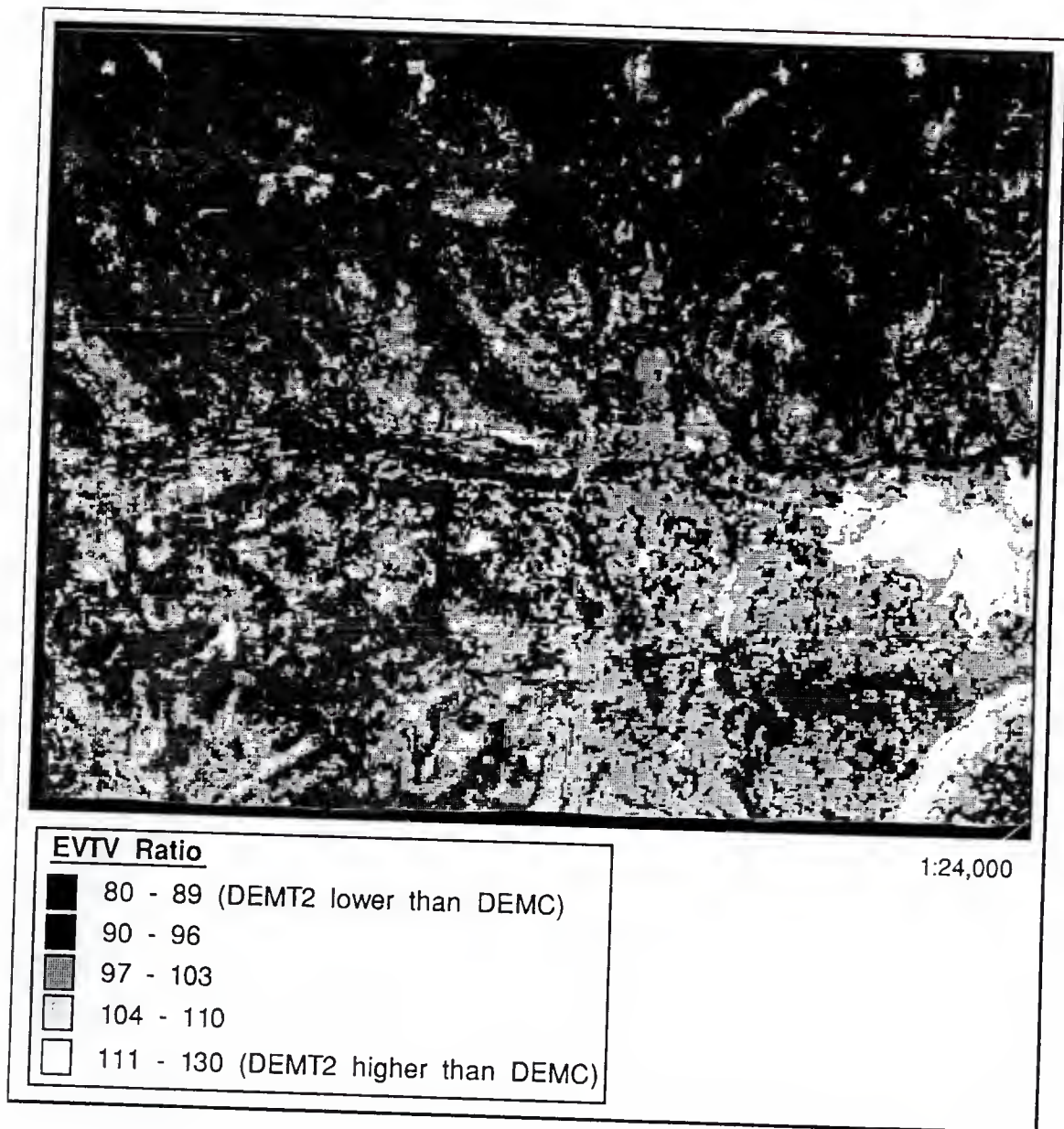


Figure 6-9  
DEMT2 EVTV Ratios

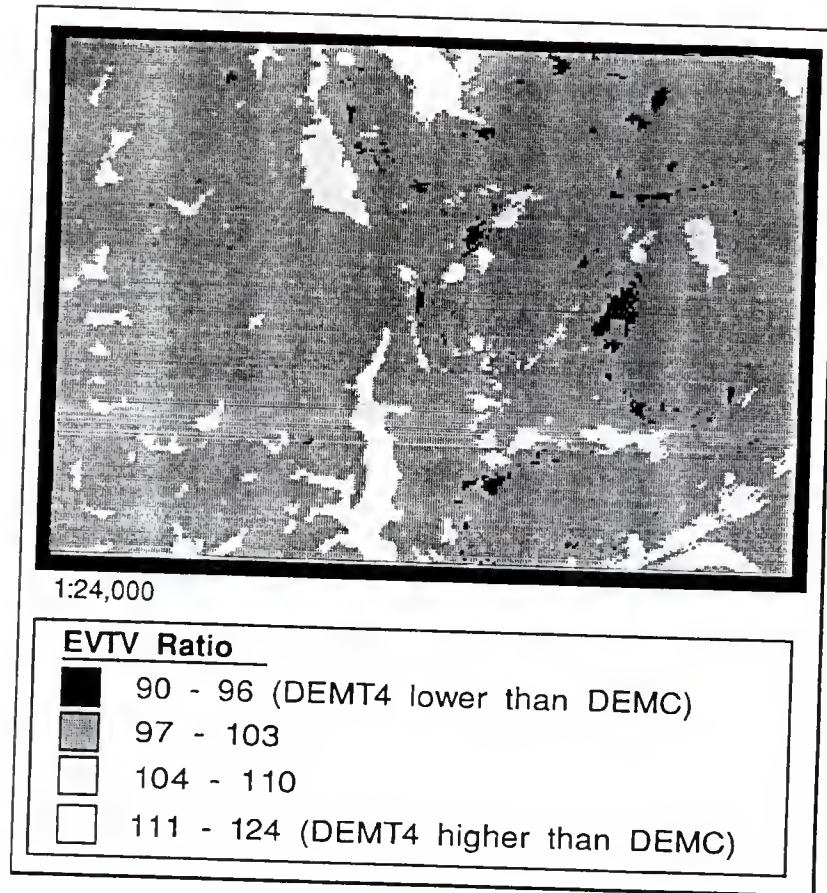


Figure 6-10  
DEMT4 EVTV Ratio

Table 6-5 shows the variation of the RMSRE for the test DEMs as well as the relative proportions of the DEMs that exhibit more or less diversity of error values. Based on DEM literature, the systematic, spatially grouped error was expected to be of lower magnitude than the random, scattered error. This was true for DEMT1 and DEMT3, which have increased RMSRE when more of the cells in the nine cell neighborhood were different from each other. But was not apparent for DEMT2 and

DEMT4, whose RMSRE values do not increase to the same degree as the other two DEMs. DEMT4 does increase some, but only a small amount, with increased diversity.

Table 6-4  
RMSRE and Landscape Characteristics

|                                                            | DEMT1       | DEMT2      | DEMT3      | DEMT4      |
|------------------------------------------------------------|-------------|------------|------------|------------|
| N Cells                                                    | 4,866,068   | 999,250    | 540,804    | 37,835     |
| Percent Slope (numbers in parentheses are percentage of N) |             |            |            |            |
| 0 -- 2%                                                    | 10.14 (9%)  | 8.53 (9%)  | 4.61 (9%)  | 0.42 (8%)  |
| 3 -- 5%                                                    | 9.92 (12%)  | 5.42 (7%)  | 4.47 (12%) | 0.88 (11%) |
| 6 -- 10%                                                   | 9.69 (21%)  | 4.84 (11%) | 4.27 (21%) | 1.09 (19%) |
| 11 -- 15%                                                  | 9.74 (19%)  | 4.80 (8%)  | 4.45 (19%) | 1.43 (14%) |
| 16 -- 20%                                                  | 10.15 (13%) | 4.57 (7%)  | 5.00 (13%) | 1.63 (12%) |
| 21 -- 25%                                                  | 11.02 (7%)  | 4.63 (6%)  | 5.93 (7%)  | 1.97 (8%)  |
| > 26%                                                      | 11.82 (20%) | 4.30 (52%) | 7.94 (20%) | 2.5 (27%)  |
| Water Cover                                                |             |            |            |            |
| Water                                                      | 18.24 (2%)  | 6.36 (2%)  | 9.30 (2%)  | 4.07 (2%)  |
| No Water                                                   | 10.18 (98%) | 5.00 (98%) | 5.37 (98%) | 2.36 (98%) |
| Tree Cover                                                 |             |            |            |            |
| Trees                                                      | 10.81 (74%) | 4.67 (88%) | 5.80 (74%) | 2.39 (92%) |
| No Trees                                                   | 8.98 (26%)  | 7.05 (12%) | 4.36 (26%) | 2.72 (8%)  |
| Elevation Height (each class % of N is about 20%)          |             |            |            |            |
| Low 1                                                      | 14.32       | 4.50       | 6.91       | 2.68       |
| 2                                                          | 13.89       | 7.41       | 8.42       | 2.02       |
| 3                                                          | 10.03       | 4.14       | 5.08       | 3.29       |
| 4                                                          | 7.72        | 4.72       | 3.49       | 2.16       |
| High 5                                                     | 5.45        | 3.63       | 3.13       | 1.61       |

| Table 6-5<br>RMSRE and Diversity of Error |                                       |             |             |             |
|-------------------------------------------|---------------------------------------|-------------|-------------|-------------|
| N of Cells of<br>Same Value               | DEMT1                                 | DEMT2       | DEMT3       | DEMT4       |
|                                           | RMSRE (percentage of region in class) |             |             |             |
| 1 - 3                                     | 9.24 (50.8)                           | 5.27 (10.6) | 2.33 (49.4) | 2.05 (1.2)  |
| 4 - 6                                     | 11.12 (39.6)                          | 4.71 (62.2) | 4.61 (46.8) | 2.27 (18.4) |
| 7 - 9                                     | 12.54 (9.6)                           | 5.44 (27.2) | 7.68 (3.9)  | 2.45 (80.4) |

The systematic error was also expected to play the larger role in terms of numbers of cells. For DEMT1 and DEMT3, this was observed, with only about 9% of DEMT1 and almost 4% of the cells falling into the highest diversity category. DEMT2 had a large number of cells that were in the middle category, of 4-6 cells of the same error value. DEMT4, was quite different from the others, with 80% of its cells falling into the most diverse category. This probably occurred because the pattern of the error was linear, following the original contour lines, and this pattern was not measurable with the nine-cell diversity measure.

### Summary of the Models

Table 6-6 summarizes the rankings of the four test DEMs for each of the assessments just considered. DEMT1 had the highest error values of all the test models. It was not as detailed as the others, and in terms of map scale, could be considered a "smaller scale" map than the others. It was most accurate in high flat places. It was least accurate in steep places. The error tended to be clustered, and the clustered error was not

of as great a magnitude as the scattered error. A DEM from SPOT imagery, such as DEMENT1, may be a cost-effective option for a large, remote area. It is probably not the best solution when other options are available.

DEMENT2, the high density DEM from high altitude photography, had a moderate magnitude of error compared with the other models. With the same scale photography,

| Table 6-6<br>Summary of Landscape Effects on the Test Models |         |           |                              |         |         |         |
|--------------------------------------------------------------|---------|-----------|------------------------------|---------|---------|---------|
|                                                              | RMSRE   | Condition | Effect of Condition on RMSRE |         |         |         |
|                                                              |         |           | DEMENT1                      | DEMENT2 | DEMENT3 | DEMENT4 |
| best                                                         | DEMENT4 | Flat      | none                         | bad     | none    | good    |
|                                                              | DEMENT2 | Steep     | bad                          | none    | bad     | bad     |
|                                                              | DEMENT3 | Water     | bad                          | bad     | bad     | bad     |
| worst                                                        | DEMENT1 | Trees     | none                         | good    | bad     | none    |
|                                                              |         | High      | good                         | none    | good    | good    |
|                                                              |         | Low       | bad                          | good    | bad     | none    |

it had lower error values, overall than the USGS model created with the GPM-2, but the USGS manual profiling DEM outperformed it. DEMENT3 had trouble with flatter areas, and it did better in very low areas than in higher ones. Automated techniques have improved since this DEM was produced, so one could assume that the error assessment results could improve, as well. With larger-scale photography, the same method should produce better results, but the cost would also increase. Overall, given the same input, DEMENT2 was competitive with the USGS DEMs.

DEMENT3 was a set of individual USGS DEMs patched together. The differences among DEMENT3, DEMENT3a and DEMENT3b illustrate that though the USGS DEMs are

standard in some ways, the method and time of production are important considerations in terms of the DEM error. The GPM-2 process (DEMT3a) did not produce as accurate of a DEM as did the manual profiling method. DEMT3, overall, was less accurate in steep areas, and individual calculations indicated that the GPM-2 portions were worse than the manual profiling in this regard. There was some clustering of low magnitude error, and the more scattered error was much higher than the clustered error. Overall, USGS DEMs are inexpensive and reliable. The standard deviation of the error was low, and the extreme errors found in DEMT1 and DEMT2 were not present in the USGS models.

DEMT4, the contour interpolated DEM, performed the best of all the models in terms of magnitude of error. There was slightly more error in the steeper areas, less in flat ones. This may reflect the graphic constraints of drawing contour lines, or it may be a result of error in the measurements from the air photos that served as input for the production of the map. The interpolation of the values represented by the contours resulted in some artifacts, with the value of the contour over-represented in the DEM. Also, the areas farthest from the contour lines was higher in magnitude than the parts closer to the contours. The clustering of error in this DEM was distinctly linear, quite different from the other DEMs. Digitizing the contours from a paper map is time-consuming and tedious, but the resultant DEM can be good enough to be worth the effort.

This chapter provided an overview of the error in each of the test DEMs. The next chapter discusses the results of the error found in viewsheds, which were produced from the DEMs. It also considered how the error in the DEMs contributed to the error in the viewsheds.

## CHAPTER VII ERROR PROPAGATION FROM DEMS TO VIEWSHEDS

### Overview of the Analysis

For the analysis outlined this chapter, the test DEMs were each subjected to a viewshed algorithm. This was done in order to estimate the viewable area from three sets of locations, or observation points, within the study area. Each set of the DEMT-derived viewsheds was compared to the comparable set of true visible areas, as calculated with the control DEM. The viewsheds were evaluated in two ways. First, they were examined in terms of the validity of the viewsheds. Second, they were assessed in light of the path of the error from the DEMs to the viewsheds. These two aspects of the analysis are reflected in the two parts in this chapter.

In the first part, the validity of the viewsheds calculated from the test DEMs was assessed. The viewsheds were compared to those calculated from DEMC and from the other test DEMs. This was done for the two subregions as defined by the limited coverage of DEMT2 and of DEMT4 as well as for the entire study area, using only DEMT1 and DEMT3. In the second part, the factors identified as being associated with the error in the test DEMs were considered in relation to the variation in the accuracy of the calculated viewsheds. This was done for the entire study area. The second part of

the chapter concludes with a description of two conceptual models which describe potential paths of the error in DEMT1 and DEMT3 to the error in the viewsheds derived from them.

### Viewshed Classification Accuracy

The control DEM and each of the test DEMs served as input for the calculation of viewsheds from each of the observation points in three different sets of observation points. Two sets of 30 observation points were randomly selected for each of two subregions, for the areas of DEMT2 and DEMT4 (Figure 7-1 and Figure 7-2). The third set of observation points consisted of 61 points from the entire study region (Figure 7-3). These were selected using stratified random sampling.

For all three sets of observation points, a 500 meter buffer around each point restricted the viewshed calculations. This was done to restrict the size of the viewsheds. For the two subregions, these buffers had to overlap in order to have space to calculate 30 viewsheds. The use of 30 viewpoints provided enough points to make a sample size from which it was possible to make statistical inferences about the results. The set of 61 points was also a large enough sample to make statistical inferences. Unlike with the sets of 30 points, the buffered areas of the set of 61 randomly selected points were not allowed to overlap. This facilitated the second part of the analysis in which the error in the DEMTs was linked to the viewshed error.

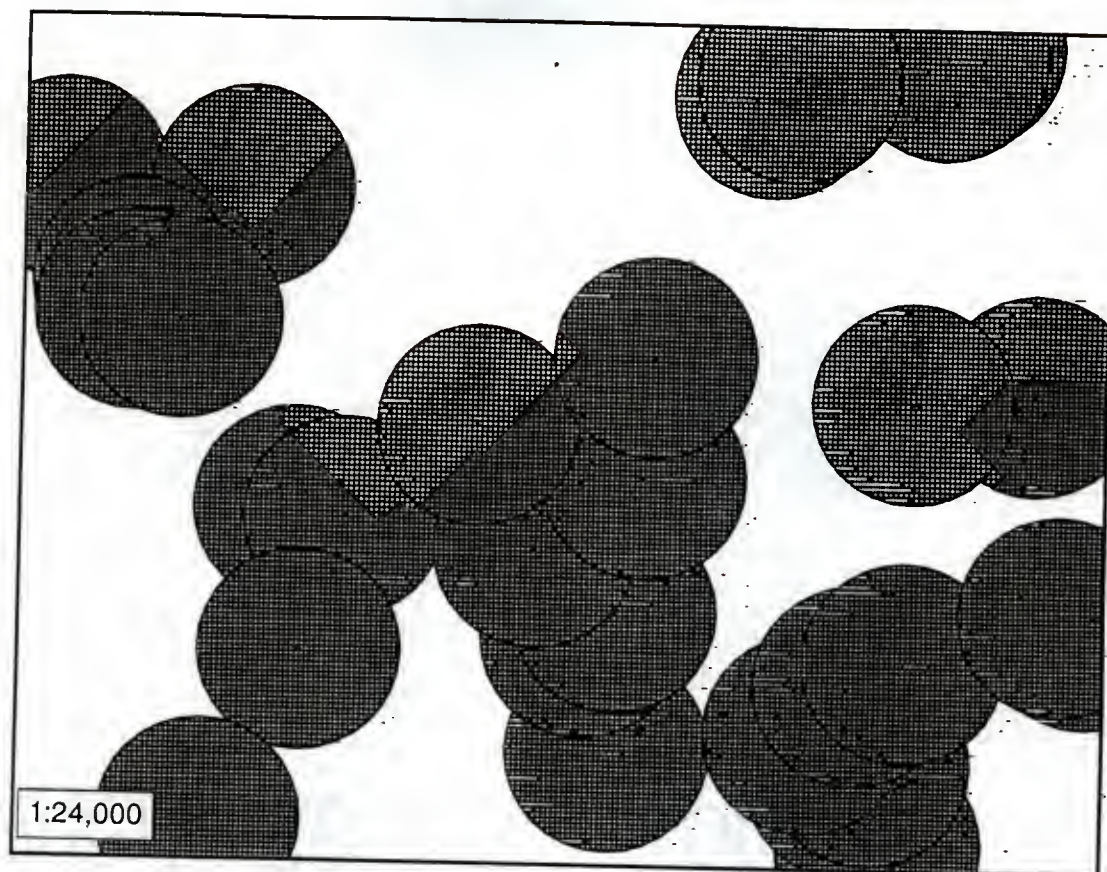


Figure 7-1  
Subregion I - 30 Observation Points with 500 Meter Buffers

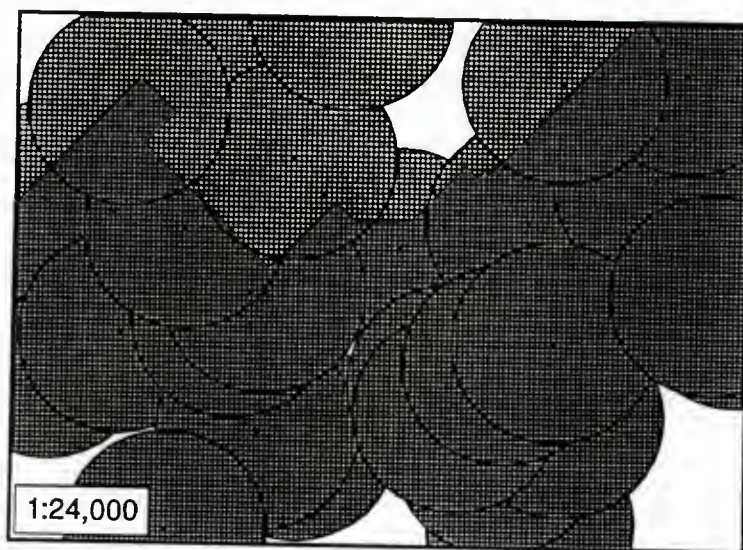


Figure 7-2  
Subregion II - 30 Observation Points with 500 Meter Buffers

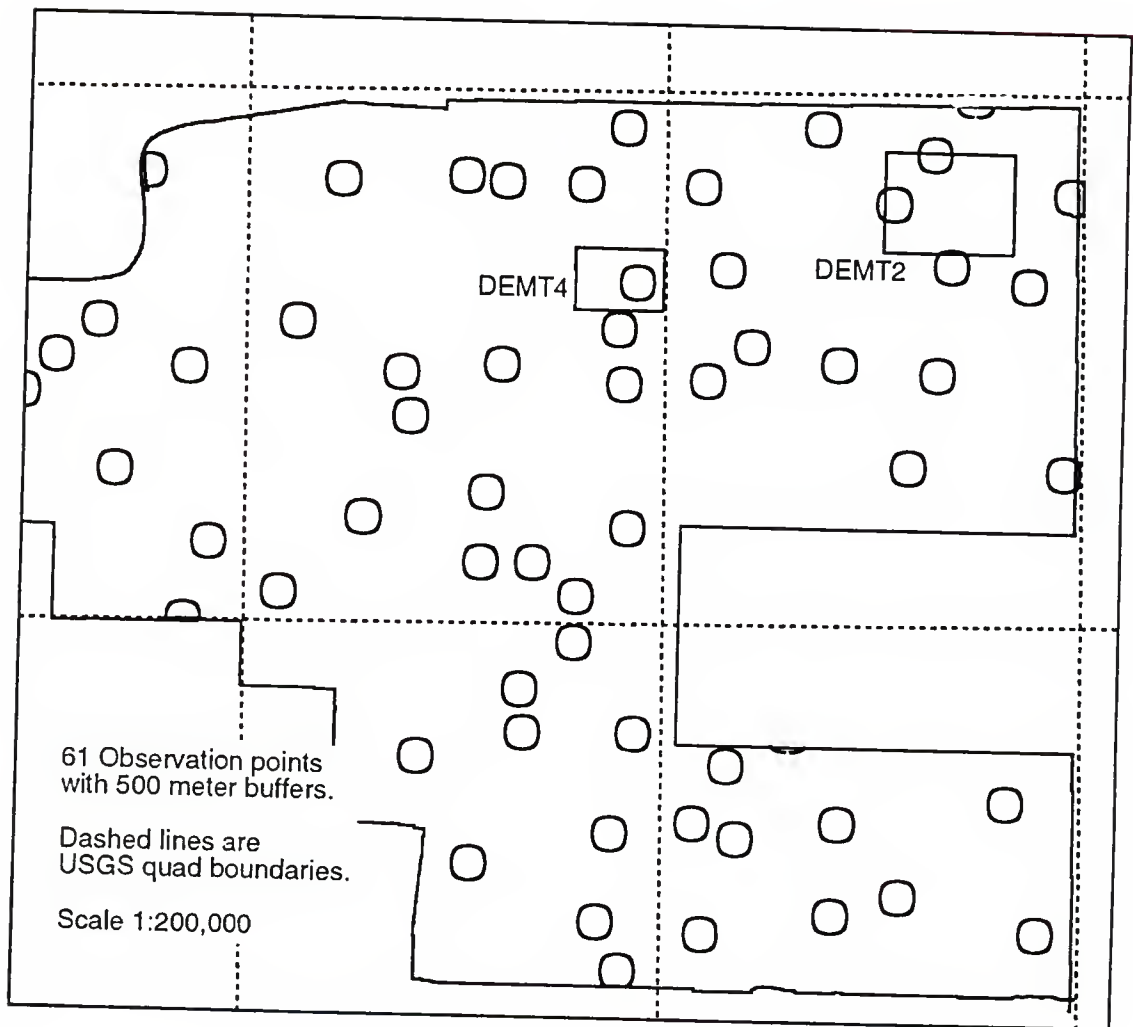


Figure 7-3  
Entire Study Area - 61 Observation Points with 500 Meter Buffers

Raster map overlays of the DEMC viewsheds and DEMT viewsheds resulted in new maps for each test DEM at each observation point. In this overlay process, the raster cells at the same location in the two maps in question -- one test and one control -- were checked for which two values coincided. This process was repeated for each of the buffered study sites. The new maps each had four classes (Figure 7-4). The four classes referred to whether the cells in the area around each observation point were correctly or incorrectly classified as visible or not visible. This type of classification was described in Chapter IV in the context of assessment of remotely sensed image classification accuracy. It was illustrated in Figure 4-1 in a more general form.

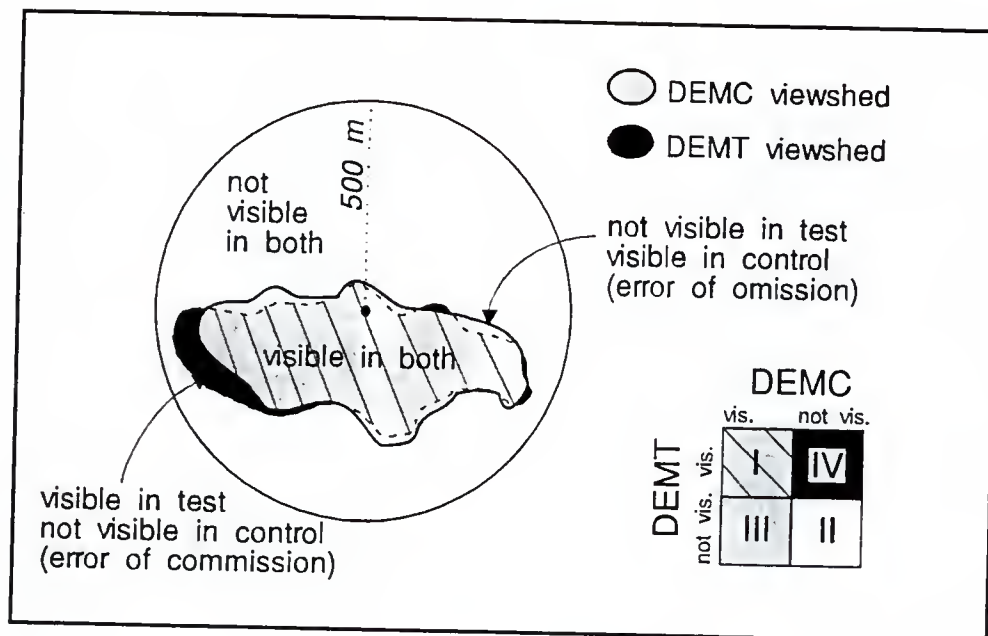


Figure 7-4  
Four Classes in Viewshed Comparisons

In Figure 7-4, around each observation point, Class I includes the cells classified by both DEMC and a DENT as visible from the observation point. Class II includes the cells classified by both the DEMC and a DENT as not visible. These first two classes, along the main diagonal of the matrix, represent the cells that are correctly classified by the test DEM. The next two classes represent the cells incorrectly classified. Class III includes cells that were classified as visible by DEMC but as not visible by the DENT. Class IV holds cells that were classified as not visible by DEMC but as visible by the DENT.

The number of raster cells that were in the four classes were arranged as contingency tables. The contingency tables for each of the DENT viewsheds compared with the DEMC viewsheds revealed the degree to which the outcomes of the viewshed analyses by the two DEMs were associated. This type of contingency table is analogous to the error matrix used in classification accuracy assessments of classified satellite imagery (Lillesand & Kiefer, 1987; Storey & Congalton, 1986).

In addition to overall levels of association, contingency tables allowed the calculation of the percentage of correctly classified cells as well as errors of omission and commission (see Chapter IV for an explanation). The following variables were calculated from the contingency tables:

pctcorrect - percent of cells correctly classified as either visible or not visible.

yo (yes omission) - percent of the truly visible cells classified as visible by the test DEM. Higher values mean that less viewable area was omitted.

no (no omission) - percent of the truly not visible cells classified as not visible by the test DEM. Higher values mean that less non-viewable area was omitted.

yc (yes commission) - percent of the cells classified by the test DEM as visible that were truly visible. Higher values mean that less of the DEMT estimated viewshed was actually not visible.

nc (no commission) - percent of the cells classified by the test DEM as not visible that were truly not visible. Higher values mean that less of the DEMT estimated not visible area was actually visible.

### Comparisons by Subregions

The subregion comparisons provided a more intensive assessment of DEMT2 and DEMT4 than could be provided by the random sample of observation points for the full study area. Since DEMT1 and DEMT3 each had full coverage of the study area, they were included in all assessments. The subregions for DEMT2 and DEMT4 are called subregion I and II respectively. For subregion I, DEMT1, DEMT2 and DEMT3 were compared to both DEMC and to each other. For subregion II, DEMT1, DEMT3 and DEMT4 were compared in a similar manner.

### DEMT1, DEMT2 and DEMT3 in subregion I

The contingency tables from the viewsheds calculated for the three test DEMs in subregion I are in Tables 7-1, 7-2 and 7-3 . This is the region associated with the coverage of DEMT2, the NHAP automated correlation model from Geospectra Corp. The other two DEMs compared with DEMT2 were DEMT1, the SPOT-derived model and DEMT3, the USGS model. Following the practice of error matrices, the control, or

reference, DEM is on the horizontal axis and the test DEMs are on the vertical axis of the tables.

| Table 7-1<br>Contingency Table for DEMENT1, Subregion I, 30 Sites |                               |                                |                                        |
|-------------------------------------------------------------------|-------------------------------|--------------------------------|----------------------------------------|
| DEMENT1                                                           | DEMC                          |                                | row total<br>percent correct           |
|                                                                   | visible                       | not visible                    |                                        |
| visible                                                           | 34,085                        | 35,120                         | 69,205<br>49.3% ( <u>yc</u> )          |
| not visible                                                       | 21,577                        | 108,277                        | 129,854<br>83.3% ( <u>nc</u> )         |
| column total<br>percent correct                                   | 55,662<br>61.2% ( <u>yo</u> ) | 143,397<br>75.5% ( <u>no</u> ) | 199,059<br>71.5% ( <u>pctcorrect</u> ) |

From Table 7-1, it can be seen that in subregion I, DEMENT1 correctly classified 71.5 percent of the cells as either visible or not visible (variable pctcorrect). Of the 55,662 truly visible cells, as defined by DEMC, 61.2 percent were correctly identified (yo). Of the 143,397 cells not visible from the observation points, 108,277 of them, or 75.5 percent were correctly identified (no). According to DEMENT1, 69,205 of the cells within the viewable regions were visible. In fact, only 34,085 of those cells were truly visible, so of the cells identified by DEMENT1 as visible, only 49.3 percent were truly visible (yc). Of the not visible cells identified by DEMENT1, 83.3 percent were correctly identified (nc).

Tables 7-2 and 7-3 may be interpreted for DEMENT2 and DEMENT3 in a similar way as was Table 7-1 for DEMENT1. From the three tables, a number of comparisons were possible. First, the DEM with the highest percentage correct was DEMENT2, the DEM from

Geospectra Corp. It classified 77.8 percent of the cells correctly. A look at the other variables for this DEM revealed an underlying problem with this DEM, however. Notably, DEMENT2 correctly classified only 35.0 percent of the truly visible cells. It had a tendency to miss large areas that were visible, wrongly classifying these areas as not visible. The ability of DEMENT2 to correctly identify the not visible areas was partly by chance, due to an overestimation of the not visible area. DEMENT3 (Table 7-3) had the same tendency. It identified only 37.1 percent of the visible cells, while it did much better with the not visible areas (92.1 percent). Overall, DEMENT3 had a total of 76.7 percent of the cells correctly identified.

Table 7-2  
Contingency Table for DEMENT2, Subregion I, 30 Sites

|                                 | DEMC                          |                                |                                        |
|---------------------------------|-------------------------------|--------------------------------|----------------------------------------|
| DEMENT2                         | visible                       | not visible                    | row total<br>percent correct           |
| visible                         | 19,495                        | 8,082                          | 27,577<br>70.7% ( <u>yc</u> )          |
| not visible                     | 36,167                        | 135,315                        | 171,482<br>78.9% ( <u>nc</u> )         |
| column total<br>percent correct | 55,662<br>35.0% ( <u>yo</u> ) | 143,397<br>94.4% ( <u>no</u> ) | 199,059<br>77.8% ( <u>pctcorrect</u> ) |

DEMENT1 (Table 7-1) had the lowest total percentage correct, with 71.5 percent of the cells correctly identified. It correctly classified 61.2 percent of the visible cells. It tended to include more cells than were visible in its visible area, however. Only 49.3 percent of the cells identified as visible were actually visible. Its overestimation of the

viewable area made it possible to classify correctly more cells as visible, but some of the correct classification is due to chance.

| Table 7-3<br>Contingency Table for DEMENT3, Subregion I, 30 Sites |                               |                                |                                        |
|-------------------------------------------------------------------|-------------------------------|--------------------------------|----------------------------------------|
| DEMENT3                                                           | DEMC<br>visible               | not visible                    | row total<br>percent correct           |
| visible                                                           | 20,664                        | 11,326                         | 31,990<br>64.6% ( <u>yc</u> )          |
| not visible                                                       | 34,998                        | 132,071                        | 167,069<br>79.1% ( <u>nc</u> )         |
| column total<br>percent correct                                   | 55,662<br>37.1% ( <u>yo</u> ) | 143,397<br>92.1% ( <u>no</u> ) | 199,059<br>76.7% ( <u>pctcorrect</u> ) |

Table 7-4 shows the results of two measures of association, which measure the strength of the relationship between the test DEMs and the control DEM. These two measures are *phi* and the contingency coefficient. They are both based on the Chi-square statistic, which tests for the independence of two variables. Chi-square ( $x^2$ ) was calculated as

$$x^2 = \sum \frac{(fo_i - fe_i)^2}{fe}$$

where  $fo_i$  is the number of observed cases (cells) within a table cell  
 $fe_i$  is the number expected for that cell.

The expected value is the product of the row and column totals for that cell divided by the total number of cases in the table.

Not surprisingly,  $x^2$  was very high for all the contingency tables, indicating that the two variables were not independent. The large sample size greatly influenced the  $x^2$

values. Of more interest were the other statistics based on  $x^2$ , that measured the strength of the relationship between the test DEMs and the control DEM, taking into account the sample size. The two statistics noted above were used for this. *Phi* was calculated as

$$\phi = \left( \frac{x^2}{N} \right)^{1/2}$$

For *phi*, a value of 0 means that no relationship exists between the two variables. A value of 1 for *phi* indicates that all cells fell in the diagonals, indicating total agreement between the two DEMs. A second measure is the contingency coefficient (C). It is also based on  $x^2$  and is calculated as

$$C = \left( \frac{x^2}{(x^2 + N)} \right)^{1/2}$$

For a two by two table, the maximum value for C is .707 and the minimum is 0. Lower values indicate a weaker relationship between the two variables and vice versa.

The differences among the DEMs in terms of the measures of association were not great. The highest value for each of the measures of association was for DEMENT2, with a *phi* value of 0.382 and C of 0.357. DEMENT1 had the lowest values, with 0.346 and 0.327, respectively, and DEMENT3 was between the other two. Significant differences among the values cannot be measured with these tests. This leads to the final part of this section, which addresses the question of whether the DEMs are any different from each other in a statistical sense.

| Table 7-4<br>Measures of Association for Contingency Tables<br>Subregion I, 30 Observation Points |          |       |                         |
|---------------------------------------------------------------------------------------------------|----------|-------|-------------------------|
|                                                                                                   | $\chi^2$ | Phi   | Contingency Coefficient |
| DEMT1                                                                                             | 23,874   | 0.346 | 0.327                   |
| DEMT2                                                                                             | 29,018   | 0.382 | 0.357                   |
| DEMT3                                                                                             | 25,393   | 0.357 | 0.336                   |

Hypothesis testing and the analysis of variance (ANOVA) technique were used to answer this question. Analysis of variance was used to test whether the variation of the percent of cells correctly classified was different for the three test models. Recall that the percent correctly classified has been measured in the variables: 1) pctcorrect; 2) yo; 3) no; 4) yc; and 5) nc. These were explained above. These five variables as measured at the 30 observation points were the dependent variables in five separate analyses. In each case, the type of DEM was the independent variable, or factor. It was suitable to use analysis of variance in this case because the variables measuring percent correctly classified were metric, while the DEM variable was nominal.

The ANOVA tested the following null hypotheses

$$H_0: M_1 = M_2 = M_3$$

The alternative hypotheses was

$$H_a: M_1 \neq M_2 \neq M_3$$

for each of the means for the five variables, pctcorrect, yo, no, yc, and nc. The level of significance was .05.

For this analysis, there was an assumption of a normal distribution of the populations and equal population standard deviations, though these may be relaxed in cases such as this one, which had equal sized groups (Clark & Hosking, 1986).

The F value was used to test the hypotheses. In the Fisher test, the difference is significant if the absolute difference between the two means is greater than the test value. Table 7-5 summarizes the results of these analyses. In cases where F was significant, a further look revealed between which DEMs the difference was found (Table 7-6).

From Table 7-5, it is clear that only three of the five null hypotheses of no difference between the means of the three test DEMs may be rejected. There was no difference among the DEMs for the variables, pctcorrect, the total percentage correctly classified and nc, the percentage of not visible area identified by the test DEM which was truly not visible. The other three variables, yo, no, and yc, each had a large enough F-value to warrant further investigation. Table 7-6 shows the results of the ANOVA for those three variables.

In all cases where differences were detected, DEMENT1 was different from the other two, while DEMENT2 and DEMENT3 did not exhibit any significant differences. DEMENT1, the SPOT-derived DEM, was the DEM that had a tendency to overestimate the visibility regions. In accordance with this tendency already mentioned in the analysis of the contingency tables, the results of the analysis of variance indicated that DEMENT2 and DEMENT3 had similar patterns of elevations, leading to similar types of viewsheds. It has also been demonstrated that while the total percentage of cells correctly identified was

similar among the DEMs, the variation of the variable pctcorrect was a function of different types of correct identification for different DEMs.

| Table 7-5                                                 |        |           |            |                                                    |
|-----------------------------------------------------------|--------|-----------|------------|----------------------------------------------------|
| F-test for One Factor ANOVA                               |        |           |            |                                                    |
| Subregion I, Count = 30                                   |        |           |            |                                                    |
| <u>pctcorrect</u> MSB=344.514 MSW=153.787 TotSS=14068.454 |        |           |            |                                                    |
|                                                           | Mean   | Std. Dev. | Std. Error | F-test                                             |
| DEMT1                                                     | 71.469 | 13.426    | 2.451      | 2.24<br>p=.1125<br>df = 89<br>(not sig.<br>at 95%) |
| DEMT2                                                     | 77.669 | 12.74     | 12.74      |                                                    |
| DEMT3                                                     | 76.94  | 10.899    | 1.99       |                                                    |
| <u>yo</u> MSB=6932.814 MSW=426.856 TotSS=51002.106        |        |           |            |                                                    |
| DEMT1                                                     | 60.809 | 20.889    | 3.814      | 16.242<br>p=.0001<br>df = 89<br>(sig. at 95%)      |
| DEMT2                                                     | 34.547 | 21.216    | 3.873      |                                                    |
| DEMT3                                                     | 34.411 | 19.852    | 3.624      |                                                    |
| <u>no</u> MSB=3048.21 MSW=111.999 TotSS=15840.325         |        |           |            |                                                    |
| DEMT1                                                     | 75.74  | 15.422    | 2.816      | 27.216<br>p=.0001<br>df = 89<br>(sig. at 95%)      |
| DEMT2                                                     | 94.453 | 4.48      | .818       |                                                    |
| DEMT3                                                     | 91.591 | 8.837     | 1.613      |                                                    |
| <u>yc</u> MSB=2035.698 MSW=613.197 TotSS=57419.547        |        |           |            |                                                    |
| DEMT1                                                     | 49.101 | 25.755    | 4.702      | 3.32<br>p=.0408<br>df = 89<br>(sig. at 95%)        |
| DEMT2                                                     | 63.787 | 26.251    | 4.793      |                                                    |
| DEMT3                                                     | 62.909 | 22.071    | 4.03       |                                                    |
| <u>nc</u> MSB=173.994 MSW=200.377 TotSS=17780.746         |        |           |            |                                                    |
| DEMT1                                                     | 82.734 | 15.107    | 2.758      | .868<br>p=.4233<br>df = 89<br>(not sig.<br>at 95%) |
| DEMT2                                                     | 78.791 | 14.485    | 2.645      |                                                    |
| DEMT3                                                     | 78.367 | 12.771    | 2.332      |                                                    |

Table 7-6  
Variables with Significant F  
One Factor ANOVA, Subregion I

| <u>yo</u>      | Mean Diff. | Fisher PLSD | Scheffe F-test |
|----------------|------------|-------------|----------------|
| DEMT1 vs DEMT2 | -26.262    | 10.603*     | 12.118*        |
| DEMT1 vs DEMT3 | 26.398     | 10.603*     | 12.244*        |
| DEMT2 vs DEMT3 | 0.137      | 10.603      | 3.283E-4       |
| <u>no</u>      |            |             |                |
| DEMT1 vs DEMT2 | 18.713     | 5.431*      | 23.451*        |
| DEMT1 vs DEMT3 | -15.851    | 5.431*      | 16.825*        |
| DEMT2 vs DEMT3 | 2.862      | 5.431       | 0.549          |
| <u>yc</u>      |            |             |                |
| DEMT1 vs DEMT2 | 14.686     | 12.708*     | 2.638          |
| DEMT1 vs DEMT3 | -13.809    | 12.708*     | 2.332          |
| DEMT2 vs DEMT3 | 0.878      | 12.708      | 0.009          |

\* Significant at 95%

#### DEMT1, DEMT3, and DEMT4 in subregion II

In this section, the same set of procedures used for the first subregion was repeated for a different area and with the contour interpolated DEM (DEMT4), instead of DEMT2. As before, the two DEMs with full coverage, DEMT1 and DEMT3, were compared to the other DEM, which was DEMT4 this time, using the area for which coverage was available.

Tables 7-7, 7-8 and 7-9 are the contingency tables for DEMT1, DEMT3, and DEMT4 for subregion II. As in subregion I, DEMT1 had the lowest value for pctcorrect, 73.6 percent. This was reflected in a similar pattern as before with a tendency to overestimate the viewsheds. DEMT3 also had similar values as for subregion I, with a

slightly higher value for pctcorrect than DEMT1, at 77.6 percent, but with a tendency to underestimate viewsheds. DEMT4 had the highest value for pctcorrect, with 78.3 percent. It had a moderate value for percent of the truly viewable area identified at 55.4 percent. The measures of associations calculated from these tables are in Table 7-10

| Table 7-7<br>Contingency Table for DEMT1, Subregion II, 30 Sites |                               |                                |                                        |
|------------------------------------------------------------------|-------------------------------|--------------------------------|----------------------------------------|
|                                                                  | DEMC                          |                                |                                        |
| DEMT1                                                            | visible                       | not visible                    | row total<br>percent correct           |
| visible                                                          | 23,980                        | 32,920                         | 56,900<br>42.1% ( <u>yc</u> )          |
| not visible                                                      | 15,176                        | 110,427                        | 125,603<br>87.9% ( <u>nc</u> )         |
| column total<br>percent correct                                  | 39,156<br>61.2% ( <u>yo</u> ) | 143,347<br>77.0% ( <u>no</u> ) | 182,503<br>73.6% ( <u>pctcorrect</u> ) |

| Table 7-8<br>Contingency Table for DEMT3, Subregion II, 30 Sites |                               |                                |                                        |
|------------------------------------------------------------------|-------------------------------|--------------------------------|----------------------------------------|
|                                                                  | DEMC                          |                                |                                        |
| DEMT3                                                            | visible                       | not visible                    | row total<br>percent correct           |
| visible                                                          | 12,843                        | 14,531                         | 27,374<br>46.9% ( <u>yc</u> )          |
| not visible                                                      | 26,313                        | 128,816                        | 155,129<br>83% ( <u>nc</u> )           |
| column total<br>percent correct                                  | 39,156<br>32.8% ( <u>yo</u> ) | 143,347<br>89.1% ( <u>no</u> ) | 182,503<br>77.6% ( <u>pctcorrect</u> ) |

The *phi* statistic and the contingency coefficient for DEMT4 were the highest of the three DEMs. They are also slightly higher than for DEMT2 (subregion I), which had values of .382 and .357 for *phi* and C respectively. DEMT3 had the lowest values for

both measures of association. The values of .261 and .252 were lower, even than the DGMT3 values for subregion I, where the two comparable values were .357 and .336. This indicates that there were differences in the viewshed calculation performance for the same DEM in different areas, where landscape and DEM characteristics vary. This will be addressed more fully in the second part of this chapter.

Table 7-9  
Contingency Table for DGMT4, Subregion II, 30 Sites

|                                 | DEMC                          |                                |                                        |
|---------------------------------|-------------------------------|--------------------------------|----------------------------------------|
| DGMT2                           | visible                       | not visible                    | row total<br>percent correct           |
| visible                         | 21,708                        | 22,234                         | 43,942<br>49.4% ( <u>yc</u> )          |
| not visible                     | 17,448                        | 121,113                        | 138,561<br>87.4% ( <u>nc</u> )         |
| column total<br>percent correct | 39,156<br>55.4% ( <u>yo</u> ) | 143,347<br>84.5% ( <u>no</u> ) | 182,503<br>78.3% ( <u>pctcorrect</u> ) |

Table 7-10  
Measures of Association for Contingency Tables  
Subregion II, 30 Observation Points

|       | $\chi^2$ | Phi   | Contingency<br>Coefficient |
|-------|----------|-------|----------------------------|
| DGMT1 | 21,000   | 0.339 | 0.321                      |
| DGMT3 | 12,390   | 0.261 | 0.252                      |
| DGMT4 | 26,824   | 0.383 | 0.358                      |

To conclude the analysis of the DEMs in subregion II, a set of analyses using ANOVA techniques addressed the question of whether the differences in means among the DEMs was significant. Tables 7-11 and 7-12 hold the results of the ANOVA.

For subregion II, the variation of the variable pctcorrect was not significantly different between the DEMs. The variables where a significant difference was measured were in yo, no, and nc. This is different from the variables in subregion I, which included yo, no, and yc. The difference in yc between DEMENT1 and DEMENT3 was not as pronounced in subregion II, as it was in I, because DEMENT3 performed much worse on that variable in subregion II (mean value of 62.909 percent in I and 51.45 percent in II), bringing down that value to about the same as DEMENT1, which had an average value of 45.16.

The inclusion of nc in the list of significant variables was not obvious from the differences in the means among the three DEMs. The reason for its inclusion appears in the more complete ANOVA results on the three DEMs in Table 7-12. The variable nc had a difference in variation between DEMENT1 and DEMENT3. This difference was the predominant feature of results from subregion I, lending further evidence to its validity. These two DEMs also exhibited differences for the other two significantly different variables, yo and no.

For the variables no and nc, DEMENT4 had mean values between the other two DEMs, and thus was not significantly different from either. Only for the variable yo did it show a difference from DEMENT3. In general, the mean values for DEMENT4 were closer to DEMENT1 than they were to DEMENT3.

To summarize the findings of the two subregions, DEMENT1 and DEMENT3 had significantly different viewsheds. DEMENT2 was essentially similar to DEMENT3. DEMENT4 was more like DEMENT1 than it was like DEMENT3. Landscape characteristics, such as

steepness of slope, and the z-value of the observation points, were constant within the subregion comparisons, so the differences observed were a function of the different patterns of the elevations in the DEMS.

| Table 7-11<br>F-test for One Factor ANOVA<br>Subregion II, Count = 30 |        |           |            |                                                     |
|-----------------------------------------------------------------------|--------|-----------|------------|-----------------------------------------------------|
| <u>pctcorrect</u> MSB=142.08 MSW=107.419 TotSS=9629.638               |        |           |            |                                                     |
|                                                                       | Mean   | Std. Dev. | Std. Error | F-test                                              |
| DEMT1                                                                 | 73.777 | 10.864    | 1.984      | 1.323<br>p=.2717<br>df = 89<br>(not sig.<br>at 95%) |
| DEMT3                                                                 | 77.065 | 9.127     | 1.666      |                                                     |
| DEMT4                                                                 | 77.89  | 10.997    | 2.008      |                                                     |
| <u>yo</u> MSB=5980.843 MSW=355.906 TotSS=42925.533                    |        |           |            |                                                     |
| DEMT1                                                                 | 58.813 | 19.18     | 3.502      | 16.805<br>p=.0001<br>df = 89<br>(sig. at 95%)       |
| DEMT3                                                                 | 32.119 | 17.717    | 3.235      |                                                     |
| DEMT4                                                                 | 53.445 | 19.645    | 3.587      |                                                     |
| <u>no</u> MSB=1114.675 MSW=162.362 TotSS=16354.806                    |        |           |            |                                                     |
| DEMT1                                                                 | 77.382 | 14.057    | 2.566      | 6.865<br>p=.0017<br>df = 89<br>(sig. at 95%)        |
| DEMT3                                                                 | 89.567 | 10.026    | 1.831      |                                                     |
| DEMT4                                                                 | 83.798 | 13.746    | 2.51       |                                                     |
| <u>yc</u> MSB=592.068 MSW=424 TotSS=38072.158                         |        |           |            |                                                     |
| DEMT1                                                                 | 45.16  | 20.566    | 3.755      | 1.396<br>p=.253<br>df = 89<br>(not sig.<br>at 95%)  |
| DEMT3                                                                 | 51.45  | 19.105    | 3.488      |                                                     |
| DEMT4                                                                 | 53.74  | 22.001    | 4.017      |                                                     |
| <u>nc</u> MSB=204.361 MSW=64.543 TotSS=6023.932                       |        |           |            |                                                     |
| DEMT1                                                                 | 87.375 | 7.451     | 1.36       | 3.166<br>p=.0471<br>df = 89<br>(sig at 95%)         |
| DEMT3                                                                 | 82.505 | 8.652     | 1.58       |                                                     |
| DEMT4                                                                 | 86.567 | 7.953     | 1.452      |                                                     |

Table 7-12  
One Factor ANOVA, Subregion II  
Variables with Significant F-test

| <u>yo</u>      | Mean Diff. | Fisher PLSD | Scheffe F-test |
|----------------|------------|-------------|----------------|
| DEMT1 vs DEMT3 | 26.694     | 9.682*      | 15.016*        |
| DEMT1 vs DEMT4 | - 5.368    | 9.682       | .607           |
| DEMT3 vs DEMT4 | 21.326     | 9.682*      | 9.58*          |
| <u>no</u>      |            |             |                |
| DEMT1 vs DEMT3 | -12.185    | 6.539*      | 6.859*         |
| DEMT1 vs DEMT4 | 6.416      | 6.539       | 1.902          |
| DEMT3 vs DEMT4 | - 5.769    | 6.539       | 1.537          |
| <u>nc</u>      |            |             |                |
| DEMT1 vs DEMT3 | 4.87       | 4.123*      | 2.756          |
| DEMT1 vs DEMT4 | - 0.809    | 4.123       | .076           |
| DEMT3 vs DEMT4 | 4.062      | 4.123       | 1.917          |

\* Significant at the 95% level

On the other hand, comparisons between the subregions were made for different sets of observation points. The effect of the landscape characteristics and the z-values of the observation points may have influenced the differing ability of the DEMs to produce viewsheds. For that reason, direct comparison of DEMT2 and DEMT4 was not possible. The issue of how the characteristics of the area and the error in the DEMs affects the viewshed will be covered in the second part of this chapter.

#### DEMT1 and DEMT3 for the entire study area

This final comparison was for DEMT1 and DEMT3 across the entire study area. This comparison was included as a preface to the next part of the analysis which included the development of a conceptual model of the path of error in a DEM to the error in

viewshed calculations. It also served as further evidence of the difference between the two test DEMs, which was already observed in the first part of the analysis, for the two subregions. First, Tables 7-13 and 7-14 are the contingency tables for the cells classified for the 61 observation points included in this assessment.

| Table 7-13<br>Contingency Table for DGMT1, Entire Study Area, 61 Sites |                               |                                |                                        |
|------------------------------------------------------------------------|-------------------------------|--------------------------------|----------------------------------------|
|                                                                        | DEMC                          |                                | row total<br>percent correct           |
| DEMT1                                                                  | visible                       | not visible                    |                                        |
| visible                                                                | 56,938                        | 89,562                         | 146,500<br>38.9% ( <u>yc</u> )         |
| not visible                                                            | 37,333                        | 275,055                        | 312,388<br>88.0% ( <u>nc</u> )         |
| column total<br>percent correct                                        | 94,271<br>60.4% ( <u>yo</u> ) | 364,617<br>75.4% ( <u>no</u> ) | 458,888<br>72.3% ( <u>pctcorrect</u> ) |

| Table 7-14<br>Contingency Table for DGMT3, Entire Study Area, 61 Sites |                               |                                |                                        |
|------------------------------------------------------------------------|-------------------------------|--------------------------------|----------------------------------------|
|                                                                        | DEMC                          |                                | row total<br>percent correct           |
| DEMT3                                                                  | visible                       | not visible                    |                                        |
| visible                                                                | 28,032                        | 29,472                         | 57,504<br>48.7% ( <u>yc</u> )          |
| not visible                                                            | 66,239                        | 335,145                        | 401,384<br>83.5% ( <u>nc</u> )         |
| column total<br>percent correct                                        | 94,271<br>29.7% ( <u>yo</u> ) | 364,617<br>91.9% ( <u>no</u> ) | 458,888<br>79.1% ( <u>pctcorrect</u> ) |

| Table 7-15<br>Measures of Association for Contingency Tables<br>Entire Study Area, 61 Observation Points |          |       |                         |
|----------------------------------------------------------------------------------------------------------|----------|-------|-------------------------|
|                                                                                                          | $\chi^2$ | Phi   | Contingency Coefficient |
| DEMT1                                                                                                    | 44,260   | 0.311 | 0.297                   |
| DEMT3                                                                                                    | 32,040   | 0.264 | 0.288                   |

DEMT3 had a higher value of pctcorrect, at 79.1 percent. DEMT1 classified about 72 percent of the cells correctly. Once again, DEMT1 classified correctly many more of the visible cells than did DEMT3, 60.4 percent compared to only 29.7 percent. DEMT3 certainly had trouble identifying all of the truly visible area. Of that which it did identify as visible, only 48.7 percent was truly visible. For DEMT1, it was even lower, at only 38.9 percent.

The ANOVA tables follow in Table 7-16. Unlike in the previous two examples, all of the dependent variables proved to be significant, so all of the results are reported in one table. The histograms of the distribution of the variables used in these tests are in the Appendix.

The two DEMs were significantly different for all variables when the observation points were selected over a larger, more diverse, area but were not when the points were selected for more restricted areas. This suggests that either the DEMs, themselves, were not created under the same model from place to place, or that the landscape characteristics of the different areas influenced the error in the DEMs and, in turn affected the viewsheds. These questions are addressed in the next section.

Table 7-16  
ANOVA Results for Entire Study Area, 61 Observation Points

| <u>pctcorrect</u>                                               | Mean       | Std. Dev.   |           |
|-----------------------------------------------------------------|------------|-------------|-----------|
| DEMT1                                                           | 71.941     | 10.003      |           |
| DEMT3                                                           | 78.89      | 10.335      |           |
| F-test 14.111<br>p = .0003 df = 121                             | Mean Diff  | Fisher PLSD | Scheffe F |
|                                                                 | 6.949      | 3.663*      | 14.111*   |
| <u>yo</u>                                                       | Mean       | Std. Dev.   |           |
| DEMT1                                                           | 62.195     | 18.578      |           |
| DEMT3                                                           | 33.421     | 19.014      |           |
| F-test 71.467<br>p = .0001 df = 121                             | Mean Diff. | Fisher PLSD | Scheffe F |
|                                                                 | -28.774    | 6.739*      | 71.467*   |
| <u>no</u>                                                       | Mean       | Std. Dev.   |           |
| DEMT1                                                           | 75.002     | 11.417      |           |
| DEMT3                                                           | 91.484     | 7.574       |           |
| F-test 88.278<br>p = .0001 df = 121                             | Mean Diff. | Fisher PLSD | Scheffe F |
|                                                                 | 16.482     | 3.473*      | 88.278*   |
| <u>yc</u>                                                       | Mean       | Std. Dev.   |           |
| DEMT1                                                           | 38.903     | 17.921      |           |
| DEMT3                                                           | 53.175     | 21.046      |           |
| F-test 16.262<br>p = .0001 df = 121                             | Mean Diff. | Fisher PLSD | Scheffe F |
|                                                                 | 14.272     | 7.007*      | 16.262*   |
| <u>nc</u>                                                       | Mean       | Std. Dev.   |           |
| DEMT1                                                           | 87.59      | 10.569      |           |
| DEMT3                                                           | 83.31      | 11.463      |           |
| F-test 4.597<br>p = .034 df = 121<br>* significant at 95% level | Mean Diff. | Fisher PLSD | Scheffe F |
|                                                                 | - 4.28     | 3.952*      | 4.597*    |

### From Error in DEMs to Error in Viewsheds

Now, it is time to address the question of how the error in the DEMs affects the outcome of the viewsheds. A conceptual model based on the available data is presented here. DEMENT1, the SPOT-derived DEM and DEMENT3, the USGS DEM, were the basis for the final analysis. The 61 observation points and the 500 meter buffer around each point served as the sample for this part.

#### Correlations Among the Variables

Three sets of variables were considered for this analysis. The first group were the five viewshed variables used in the previous assessment. As before, these were called pctcorrect, yo, no, yc, and nc. Companions to these was the z-value, or height, of the observation points and the average elevation of the area. Fisher's (1992) work with viewsheds suggested strongly that the height of the viewpoint was the only variable of predictive power in his examination of viewshed uncertainty.

The second group was the landscape variables. These included steepness of slope (slope) and tree cover (trees). It was noted in the last chapter that steepness of slope had an adverse effect on the accuracy of the test DEMs (Table 6-4). Two of the DEMs, DEMENT1 and DEMENT2 also had error of greater magnitude in flatter areas. This may have occurred because of some other factor, which was correlated with slope steepness. Water is more likely to be present in flat areas, for example, and in the study area, steeper areas

were more likely to have heavy tree cover. Both of these two variables, water and tree cover, could also affect the DEM, independently of slope steepness.

How the landscape variables could affect the viewshed calculations was not clear. Rough areas may pose more difficulty for the viewshed algorithm, and the result, being more complex, had more room for error. It was also possible that the landscape variable may have affected the error in the DEMs in a consistent manner that then led to smoothing or artifacts, which, in turn, affected the viewshed calculation.

The third set of variables included the two which measured the magnitude and spatial clustering of the error in the DEMs (Tables 6-3 and 6-5). The root mean square ratio error (RMSRE) and the diversity of the error in the DEMs were expected to have an effect on the viewshed calculations. At the same time, given the findings in the previous chapter and section, this may not be as clear a relationship as first imagined.

Table 7-17 lists the variables of interest for this analysis. The variables were measured for each of the 61 observation point areas. Histograms of the distributions of the variables not yet illustrated are in the Appendix. The z-value is a point measure. The viewshed variables were the percentage correct for each of the areas, as presented in the first part of this chapter. The slope steepness variable was the average percent slope in the viewshed areas. Higher values indicated an area where slopes were generally steep, and lower values were found in places which were generally flat. Tree cover was measured as the percentage of the area covered by trees. The RMSRE value and the diversity measure were calculated as averages for each of the 61 areas.

The first step in development of the model was to examine the correlation coefficients among the variables. The values of Pearson's correlation coefficient, usually called  $r$ , for each of the possible pairs of variables are in the correlation matrices in Table 7-18 and 7-19. DEMENT1 is represented in the first and DEMENT3 in the second matrix.

| Table 7-17<br>Variables Used in Models of Error |                                                                           |
|-------------------------------------------------|---------------------------------------------------------------------------|
| Variable Name                                   | Description of Variable                                                   |
| <u>pctcorrect</u>                               | Percentage of cells correctly classified                                  |
| <u>yo</u>                                       | Percentage of truly visible cells correctly classified                    |
| <u>no</u>                                       | Percentage of truly not visible cells correctly classified                |
| <u>yc</u>                                       | Percentage of cells classified as visible that were truly visible         |
| <u>nc</u>                                       | Percentage of cells classified as not visible that were truly not visible |
| RMSRE                                           | Root mean square ratio error                                              |
| <u>evtv.div</u>                                 | Average diversity of the EVTV ratio                                       |
| <u>trees</u>                                    | Percentage of area covered by trees                                       |
| <u>slope</u>                                    | Average steepness of slope                                                |
| <u>z</u>                                        | Height of observation point                                               |
| <u>z.ave</u>                                    | Average elevation                                                         |

The correlation matrices in Tables 7-18 and 7-19 revealed a rich set of intercorrelations among the variables. The relationships were of three types. First, there were relationships that occurred because of the particularities of the area in question. For example, the coefficient between the variables trees and slope ( $r=.48$ ) indicated that trees

tended to be more abundant in areas with rougher terrain. Trees were also more abundant in lower areas than in higher ones (trees and z.ave,  $r=-.371$ ). These relationships served to describe the natural area of Fort Knox, Kentucky, and since DEM error is tied to such variables, were important components of a model of DEM error.

A second type of relationship existed between the natural variables and the DEMs. Many of these were already observed in the overview of DEM error in Chapter VI (Table 6-4). For example, values of RMSRE for DEMT1 and DEMT3 were both positively related to slope, with  $r$  values of about .6 for each DEM. In terms of tree cover, the RMSRE of both of the DEMs was positively correlated with tree cover, but only with DEMT3 was the coefficient significant at the 95% level.

In both DEMs, the RMSRE was inversely related to elevation values. The relationship was stronger for DEMT1. For DEMT1, the  $r$  value was  $-.545$  for the average  $z$  values and for DEMT3, that value was  $-.137$ . This reflects the pattern observed in Table 6-4, which showed a consistent increase in RMSRE with increased height in DEMT1, but a pattern that is much less clear for those two values in DEMT3.

The effect of diversity on the error values was also an issue addressed earlier (Table 6-5). Given the findings when the entire DEMs were assessed, which showed an increase in RMRSE in those neighborhoods with more diversity, it was not surprising that both DEMT1 and DEMT3 had strong positive relationships between the diversity and the RMSRE variables. Further, the earlier finding that the pattern was more pronounced with DEMT3 than with DEMT1 was also reaffirmed, with  $r$  values of .871 and .665 for DEMT3 and DEMT1, respectively.

Table 7-18  
Correlation Matrix for DENT1 for All Variables

|                | <u>pctcor.</u> | <u>yo</u> | <u>no</u> | <u>yc</u> | <u>nc</u> | RMSRE  | <u>div</u> |
|----------------|----------------|-----------|-----------|-----------|-----------|--------|------------|
| <u>pctcor.</u> | 1.0            | 0.28*     | 0.845*    | 0.373*    | 0.519*    | 0.15   | 0.26*      |
| <u>yo</u>      | 0.28*          | 1.0       | -0.177    | 0.113     | 0.61*     | 0.414* | 0.456*     |
| <u>no</u>      | 0.845*         | -0.177    | 1.0       | 0.456*    | 0.122     | -0.064 | 0.01       |
| <u>yc</u>      | 0.373*         | 0.113     | 0.456*    | 1.0       | -0.377*   | 0.077  | 0.173      |
| <u>nc</u>      | 0.519*         | 0.61      | 0.122     | -0.377*   | 1.0       | 0.246* | 0.278*     |
| RMSRE          | 0.15           | 0.414*    | -0.064    | 0.077     | 0.246*    | 1.0    | 0.665*     |
| <u>div.</u>    | 0.26*          | 0.456     | 0.01      | 0.173     | 0.278*    | 0.665* | 1.0        |
| <u>trees</u>   | 0.129          | 0.021     | 0.134     | 0.268*    | -0.124    | 0.235* | 0.53*      |
| <u>slope</u>   | 0.389*         | 0.52*     | 0.075     | 0.167     | 0.417*    | 0.627* | 0.938*     |
| <u>z</u>       | 0.406*         | 0.139     | 0.248*    | -0.176    | 0.557*    | -0.062 | -0.173     |
| <u>z-ave</u>   | 0.298*         | 0.167     | 0.095     | -0.317*   | 0.586*    | -0.137 | -0.251*    |

Table 7-18--continued

|                | <u>trees</u> | <u>slope</u> | <u>z</u> | <u>z-ave</u> |
|----------------|--------------|--------------|----------|--------------|
| <u>pctcor.</u> | 0.129        | 0.389*       | 0.406*   | 0.298*       |
| <u>yo</u>      | 0.021        | 0.52*        | 0.139    | 0.167        |
| <u>no</u>      | 0.134        | 0.075        | 0.248*   | 0.095        |
| <u>yc</u>      | 0.268*       | 0.167        | -0.176   | -0.317*      |
| <u>nc</u>      | -0.124       | 0.417*       | 0.557*   | 0.586*       |
| RMSRE          | 0.235*       | 0.627*       | -0.062   | -0.137       |
| <u>div</u>     | 0.53*        | 0.938*       | -0.173   | -0.251*      |
| <u>trees</u>   | 1.0          | 0.48*        | 0.269*   | 0.371*       |
| <u>slope</u>   | 0.48*        | 1.0          | 0.095    | 0.034        |
| <u>z</u>       | -0.269*      | 0.095        | 1.0      | 0.893*       |
| <u>z-ave</u>   | -0.371*      | 0.034        | 0.893*   | 1.0          |

\* Significant at the 95% level

Table 7-19  
Correlation Matrix for DEMENT3 for All Variables

|                | <u>pctcor.</u> | <u>yo</u> | <u>no</u> | <u>yc</u> | <u>nc</u> | RMSRE   | <u>div</u> |
|----------------|----------------|-----------|-----------|-----------|-----------|---------|------------|
| <u>pctcor.</u> | 1.0            | 0.228     | 0.491*    | 0.039     | 0.884*    | -0.118  | 0.013      |
| <u>yo</u>      | 0.228          | 1.0       | -0.512*   | -0.217    | -0.217    | -0.329* | -0.211     |
| <u>no</u>      | 0.491*         | -0.512*   | 1.0       | 0.581*    | 0.084     | 0.291*  | 0.345      |
| <u>yc</u>      | 0.039          | -0.217    | 0.581*    | 1.0       | -0.312*   | 0.283*  | 0.334      |
| <u>nc</u>      | 0.884*         | 0.509*    | 0.084     | -0.312*   | 1.0       | -0.285* | -0.156     |
| RMSRE          | -0.118         | 0.066     | 0.291*    | 0.283*    | -0.285*   | 1.0     | 0.871      |
| <u>div</u>     | 0.013          | -0.211    | 0.345*    | 0.334*    | -0.156    | 0.871*  | 1.0        |
| <u>trees</u>   | -0.175         | -0.066    | 0.064     | 0.266*    | -0.232    | 0.451*  | 0.588      |
| <u>slope</u>   | 0.315*         | 0.045     | 0.358*    | 0.418*    | 0.172     | 0.636*  | 0.789      |
| <u>z</u>       | 0.588*         | 0.213     | 0.25*     | 0.017     | 0.574*    | -0.433* | -0.362     |
| <u>z-ave</u>   | 0.635*         | 0.299*    | 0.2       | -0.04     | 0.64*     | -0.545* | -0.467     |

Table 7-19--continued

|                | <u>trees</u> | <u>slope</u> | <u>z</u> | <u>z-ave</u> |
|----------------|--------------|--------------|----------|--------------|
| <u>pctcor.</u> | -0.175       | 0.315*       | 0.588*   | 0.315*       |
| <u>yo</u>      | -0.066       | 0.045        | 0.213    | 0.299*       |
| <u>no</u>      | 0.064        | 0.358*       | 0.25*    | 0.2          |
| <u>yc</u>      | 0.266*       | 0.418*       | 0.017    | -0.04        |
| <u>nc</u>      | -0.232       | 0.172        | 0.574*   | 0.172        |
| RMSRE          | 0.451*       | 0.636*       | -0.433*  | -0.545*      |
| <u>div</u>     | 0.588*       | 0.789*       | -0.362*  | -0.467*      |
| <u>trees</u>   | 1.0          | 0.48*        | -0.269*  | -0.371*      |
| <u>slope</u>   | 0.48*        | 1.0          | 0.095    | 0.034        |
| <u>z</u>       | -0.269*      | 0.095        | 1.0      | 0.893*       |
| <u>z-ave</u>   | -0.371*      | 0.034        | 0.893*   | 1.0          |

\* Significant at the 95% level

The third set of relationships has not yet been explored. These were concerned with the relationships among the five viewshed variables, the landscape variables and the DEM error variables. The contingency tables reviewed earlier revealed some important relationships. For example, for DEMT1, the strongest relationship between the variable pctcorrect and the other four viewshed variables was with the no variable ( $r=.845$ ). This may be interpreted as meaning that the percentage of cells correctly classified had a lot to do with the ability of DEMT1 to correctly identify not visible cells. On the other hand, for DEMT3, the strongest relationship was found between the variables pctcorrect and nc ( $r=.884$ ), indicating that the fact that DEMT3 not visible areas were truly not visible was strongly related to the overall correct classification of viewsheds.

Beyond these relationships among viewshed variables, were the relationships between the viewshed variables and the other variables. For example, the height of the observation point (z) and the average height of the areas (z.ave) measured a dimension found to be related to viewshed accuracy in earlier research (Fisher, 1992). For both DEMs, the height of the observation point was positively correlated with the percentage correctly classified, with an  $r$  value of .406 for DEMT1 and a value of .588 for DEMT3. Of the other viewshed variables, nc and yc in DEMT1 and yo, no, and nc in DEMT3 were also correlated significantly with either z or z.ave. Most of these were positive relationships, with more accurate viewsheds calculated from higher areas. One exception was DEMT1 and yc, where the percentage of the visible areas that were truly visible was higher in lower, rather than higher, areas.

The RMSRE values did not exhibit a clear relationship with the viewshed variables. For neither DEM was the RMSRE correlation with the percentage of cells correctly classified significant. For DEMENT1, the RMSRE had a positive relationship with yo. Thus, the higher the RMSRE, the better the more visible areas were correctly classified. This means that more error led to better viewshed calculations. For DEMENT3, the opposite was observed, with an  $r$  of  $-.329$  between yo and RMSRE. The viewshed variable nc exhibited a similar pattern, with an  $r$  of  $-.285$ . At the same time, no and yc were both positively correlated with RMSRE, once again indicating that better classifications occurred in places with higher RMSRE.

Linear regression is a common statistical tool for analyzing and testing such relationships. A single regression model, however, with one dependent variable, or even a set of such models would not provide a satisfactory picture of the variables above. The viewshed variables are related both to each other as well as to other variables. The same is true of the landscape variables and the DEM error variables. At this point, it is time to turn to the two models, one for each DEM, which link the variables in a meaningful way. The methods of path analysis guided the development of these models.

### The Models for DEMENT1 and DEMENT3

Given the observations above and the discussion of the three types of variables and relationships, the proposed models for DEMENT1 and DEMENT3 are in Figures 7-5 and 7-6. The straight lines in the figures indicate a causal path from one variable to other. All relationships are positive unless marked with "-". The curved lines indicate correlations

without causality. The correlation coefficients that were significant at the 95% level were the guide for these models. The strength of the relationships were not indicated on the model, itself. The causal path lines were reserved for those coefficients that had some basis in what is likely about the particular variables.

The form of the model was dictated by the observations made thus far regarding the variables. Starting at the bottom of the models, the pctcorrect variable was assumed to be influenced directly by the other four viewshed variables, but was only indirectly related to the other variables. In fact, using multiple regression, it was found that for DEMT1, 94 percent of the variation in pctcorrect was explained by variation in the other four viewshed variables. In DEMT3, 96 percent of the variation was explained. The results of the regressions are in Table 7-19.

With DEMT1, all four of the viewshed variables actually contributed to explaining the variation of pctcorrect. Using the magnitude of the standardized coefficient as a guide, it was noted that the variables, yo and yc did not explain as much as did no and nc. In DEMT3, yo did not have a significant role, and yc had a weak part. The variable nc, by itself, could explain much of the variation.

At the top of the models, are the landscape variables and the DEM error variables. These were separated into three parts. The variables z and z.ave, together, were a measure of height, with z contributing an exact figure and z.ave, a more general one. RMRSE, evtv.div, and slope are a second set. Although slope was also correlated with trees, and was, conceptually, a terrain variable, its strong correlations with the error variables led to its being included with the error variables as a group. The *r* for evtv.div

and slope was .938 for DEMENT1 and .789 for DEMENT3. Between RMSRE and slope, it was .627 and .636.

| Table 7-19<br>Multiple Regression of pctcorrect on <u>yo</u> , <u>no</u> , <u>yc</u> , and <u>nc</u><br>DEMENT1 and DEMENT3 |                          |                          |             |
|-----------------------------------------------------------------------------------------------------------------------------|--------------------------|--------------------------|-------------|
| DEMENT1                                                                                                                     | Adj. R <sup>2</sup> .938 | F-test 227.054 p = .0001 |             |
| Variable                                                                                                                    | Coefficient              | Std. Coefficient         | Probability |
| Intercept                                                                                                                   | -19.014                  |                          |             |
| <u>yo</u>                                                                                                                   | 0.078                    | 0.144                    | 0.0519      |
| <u>no</u>                                                                                                                   | 0.651                    | 0.743                    | 0.0001      |
| <u>yc</u>                                                                                                                   | 0.096                    | 0.171                    | 0.0181      |
| <u>nc</u>                                                                                                                   | 0.383                    | 0.405                    | 0.0001      |
| DEMENT3                                                                                                                     | Adj. R <sup>2</sup> .962 | F-test 380.933 p=.0001   |             |
| Intercept                                                                                                                   | -31.623                  |                          |             |
| <u>yo</u>                                                                                                                   | -0.039                   | -0.07                    | 0.1434      |
| <u>no</u>                                                                                                                   | 0.399                    | 0.29                     | 0.0001      |
| <u>yc</u>                                                                                                                   | 0.074                    | 0.149                    | 0.001       |
| <u>nc</u>                                                                                                                   | 0.857                    | 0.942                    | 0.0001      |

The basic form of the variables at the top and the bottom of the two models was the same for DEMENT1 and DEMENT3. The strength of certain relationships varied, but that was not included in the model at this time. The structural differences in the models came at the interface between the top and bottom variables. The interface for each of the models is discussed separately.

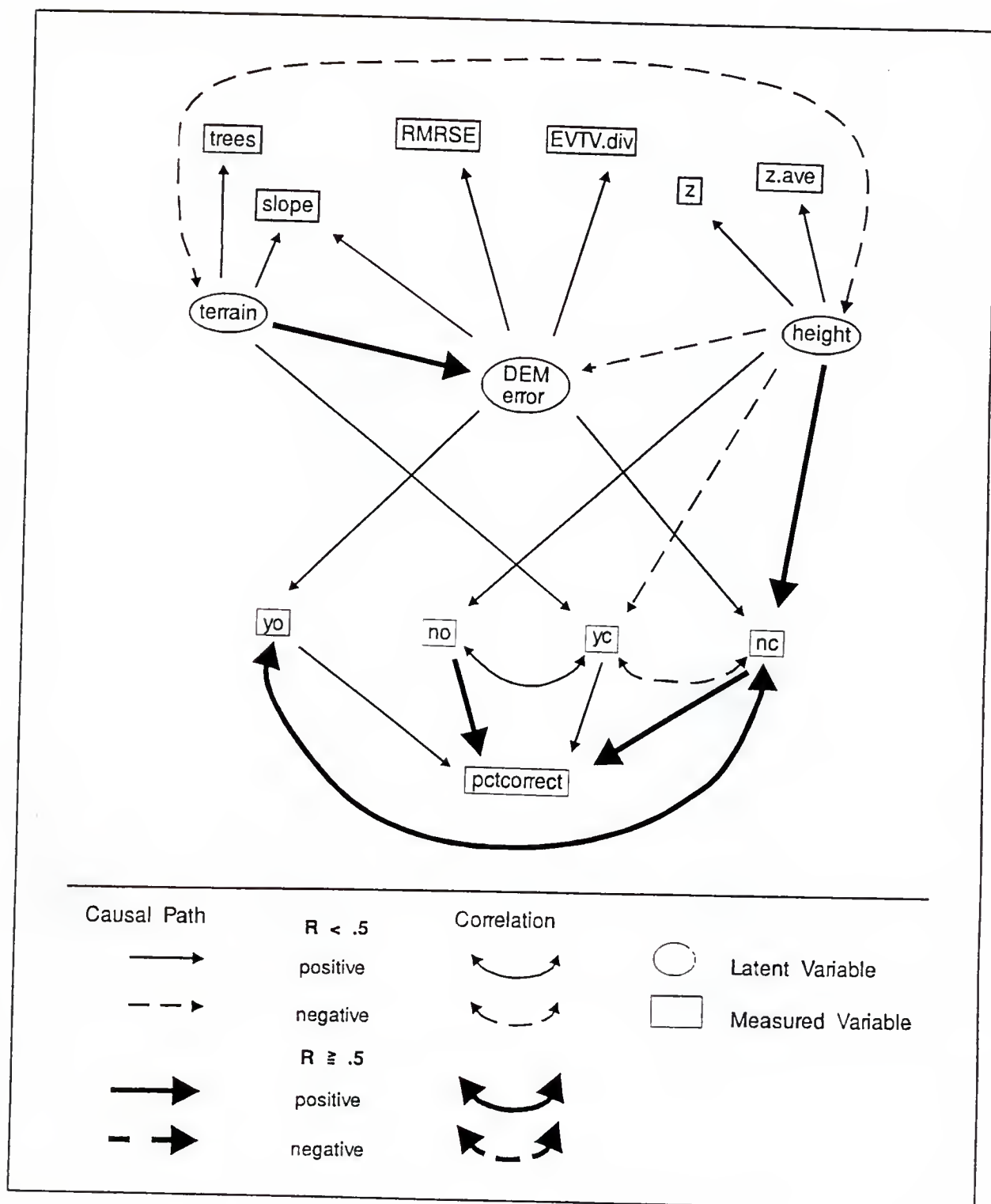


Figure 7-5  
Error Propagation Model for DEMT1

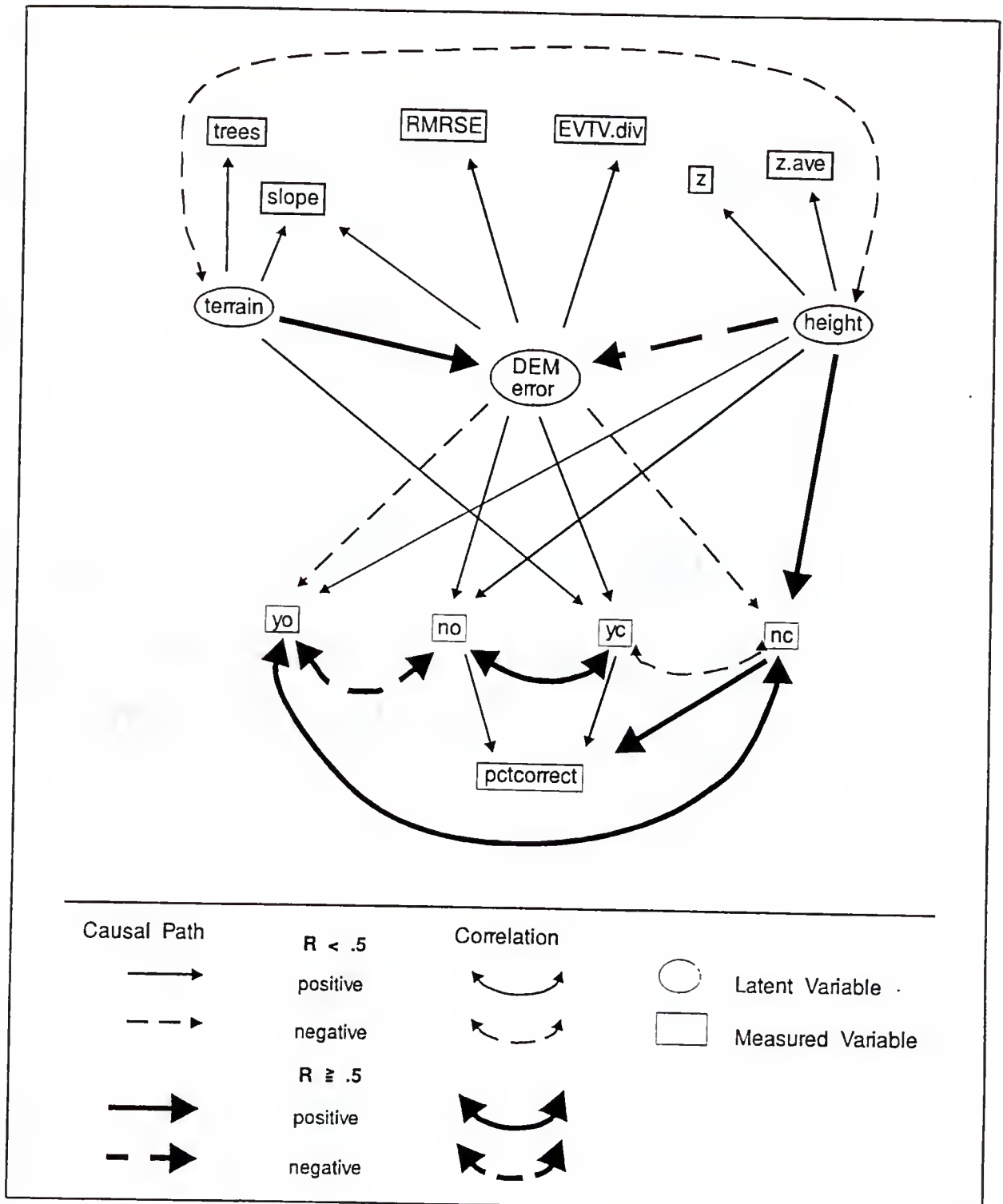


Figure 7-6  
Error Propagation Model for DEMENT3

### The DENT1 Model

Note that a higher error factor led to a higher percent correctly classified for yo and for nc. At first, this seemed counterintuitive. Why should more error in the DEM lead to a better viewshed? The probable explanation goes back to the tendency of the SPOT DEM to overestimate visible area. In places with greater error, the DEM successfully classified the visible area. At the same time, those same places have a relatively restricted, but correct not visible area. Thus, the error factor also caused higher values of nc, and nc and yc correlated positively with each other. The negative outcome of this may be seen at the negative correlation between nc and yc. This indicated that those places where visible area had been overestimated suffered from lower reliability of the areas that were identified as visible. Another outcome occurred with no, which was positively correlated with yc. This means that the places with reliable visible areas occurred along with areas where more of the not visible areas had been classified as such. Since no played a leading part in explaining the percentage correct, at this point, the proper classification can be seen as truly positive, and not just by chance, due to the type of error in the DEM.

The height variable was more directly responsible for the good viewshed outcomes than was RMRSE. The height factor caused a positive outcome in the two variables that contributed the most to pctcorrect, that is, no and nc. With yc, the height factor was negatively correlated. This means that in lower places, the reliability of the viewshed areas classified as visible was lower. This may reflect the fact that in lower areas, the error factor was generally higher, an effect carried through nc to yc.

The terrain factor seemed to cause a similar effect to the error factor. It was positively correlated with yc, meaning that rough places with trees actually produced more reliable visible areas. The variable yc was relatively less important in explaining pctcorrect compared to no and nc. Its importance may be seen in the way it correlates with the two more significant variables.

### The DENT3 Model

In this model, the error factor had a positive relationship with the viewshed variables no and yc, and a negative relationship with yo and nc. This means that in the DENT3 viewsheds, places where a higher percentage of the not visible area was identified occurred in places with higher DEM error. This reflected the tendency of the USGS DEM to overestimate the not visible area. The correlate to that was found in yc. The area that was classified as visible, while underestimated overall, was relatively reliable for what was classified.

The drawback of this tendency was seen in the negative correlations between no and yo and between yc and nc. The correctly classified areas came at the expense of the other aspects of viewshed classification being lower. The negative correlation between the error factor and yo and nc confirmed that the higher error was indicative of poorer viewshed classifications.

The height factor once again had the strongest relationship with the viewshed factor that was most strongly related to the total percentage correctly classified. In this case, that was nc. Height was also positively correlated with the second strongest variable

explaining pctcorrect, no, and with the variable yo, which had no direct effect on pctcorrect. As with DEMT1, the height factor seemed to have a more direct role in predicting pctcorrect than did DEM error.

As with DEMT1, the terrain factor had a positive relationship with yc. This means that in places where the terrain was rough and tree covered, a relatively high percentage of the area classified as visible was truly visible. The reason for this relationship was not clear from the diagram, but it is possibly tied to the inter-relationships among the terrain, error and viewshed variables.

### Conclusion

This chapter revealed a number of important aspects of viewshed error and its relationship with DEM error. First, viewshed error may be in the form of errors of omission or of commission. The four viewshed variables, yo, no, yc, and nc, each had a part to play in contributing toward the overall performance of the DEM's viewshed calculation, as measured by pctcorrect. The tendency of the DEMs to either over- or underestimate the visible area gave to the DEM a signature of error. Of the four DEMs, DEMT1 was more like DEMT4, and DEMT2 was more like DEMT3. DEMT1 and DEMT3 were distinctly different from each other.

In terms of how well the test DEMs calculated the same viewsheds as DEMC, the contingency coefficients for Subregions I and II, revealed the following. The best of the DEMTs was DEMT4, while DEMT2 was a very close second place. For DEMT1 and

DEMT3, they performed differently in the two subregions. DEMT1 was better in subregion II, and DEMT3 was better in subregion I. DEMT3 did much worse, overall, in subregion II than it did in subregion I, suggesting its susceptibility to landscape characteristics as they varied between the two subregions.

DEMT2 and DEMT4, the two DEMs with better viewsheds, also had lower error magnitude than did DEMT1 and DEMT3 (Table 6-3). The relationship between DEM error magnitude and error in the viewsheds was not clear for DEMT1 and DEMT3. As was revealed by the model development for DEMT1 and DEMT3, the height factor seemed to have as much as or greater part to play in explaining the variation in viewsheds as did error in the DEMs.

## CHAPTER VIII

### CONCLUSIONS AND RECOMMENDATIONS

This final chapter has two sections. The first part is a summary of the major findings of the research. This section is written as a simplified interpretation of the model development and the significance of the findings to users of GIS. In the second part are suggestions for possible future research. The need continues for expanding the knowledge about error in digital cartographic databases and deepening the understanding of the significance of that error in the context of a GIS.

#### Summary of the Findings

##### Error Magnitude

This research demonstrated that different methods of DEM production produced distinctly different viewshed regions, given the same observation points. This should alert GIS analysts to the potential problems with their DEM--based GIS output. They should be especially aware of whether the model that they are using may be likely to be very smooth or to include artifacts. The magnitude and pattern of the error in the DEMs also varied for the different test models. An overview of these comparisons follows.

The contour interpolated DEM (DEMT4) performed quite well in terms of error magnitude and in terms of the viewshed outcome. This DEM was able to outperform all of the other DEMs in term of RMSRE and the percent of the viewshed areas that was correctly classified as visible or not visible. It was something of a surprise to find that this was the case, especially given the relatively simple inverse distance weighted interpolation algorithm that was used. As more digitized contour map files become available and computing power increases, GIS users should have increased opportunities to create their own DEMs from these files. The more recent DEMs from the USGS, which are being interpolated from hypsographic DLGs, should also prove to be an excellent source of high quality DEMs.

The relatively poor performance of the SPOT--derived DEM (DEMT1) was disappointing. The range of error was especially high, and the shaded relief rendition of that DEM was much less detailed than the other DEMs. The relatively expensive SPOT--derived DEM should be used only when other options are not available for intermediate scale mapping. A standardization of DEM resolution information would be of great help to GIS users. The ten meter cell size of the SPOT DEM may lead some to believe that the content of the DEM is higher than that of the USGS DEMs at 30 meters. Yet, in this research, the 30 meter DEM had higher quality information than the ten meter DEM. Since map scale and resolution are related, perhaps DEMs should be labeled with information about both the horizontal resolution and something about the nominal map scale and potential contour interval of the data in the DEM.

The USGS DEM (DEMT3) was a composite of quad--based models produced by either manual profiling or the GPM-2. The USGS DEMs revealed different patterns of error for the different production methods used to create them. The one quad in the study area where the DEM was produced by manual profiling had a lower magnitude of error than did the quads produced by the GPM-2. In addition, the patches used in the GPM-2 production process resulted in a visible pattern in the quads where this method was used. Possible systematic differences in the viewshed outcomes from the two production methods were not addressed in this project.

The high density DEM produced by automated methods from high altitude air photos (DEMT2) was about on par with the USGS GPM-2 DEMs in terms of magnitude of error. This DEM, which was distributed at a three meter horizontal resolution, was another example of how the horizontal resolution of the DEM is little indication of the quality of the information found in the DEM. A commercial product such as this one, which competes with the 30 meter USGS DEM, would be hard--pressed to sell their product for places where a USGS model is available at little or no cost.

The error in the DEMs was related to number of landscape factors. The presence of water resulted in higher errors for all of the DEMs. The presence of trees did not result in higher errors in three of the DEMs, though it did adversely affect quality of the USGS DEMs. In several cases, higher places had lower errors, and low ones had higher errors. The positive effect of high places was most pronounced in the SPOT DEM. The effect of slope steepness was, generally, as expected, based on literature in DEM errors. For all but the high density DEM, steep areas were associated with higher magnitude of

error. The opposite effect of low being associated with less error, was not consistently true, however. Only the contour interpolated DEM demonstrated this quality.

### Viewshed Error

The ability of the test DEMs to produce valid viewsheds was assessed for two subregions and for the entire study area. The two subregions encompassed the smaller areas of coverage of the contour interpolated DEM and the high density DEM. The contour interpolated DEM performed the best, overall, and the SPOT--derived DEM performed the worst. The differences in the total percentage of the area correctly classified as visible or not visible were not statistically significant, however. The differences in the DEMs' viewsheds were found in the errors of omission and commission, as described below.

The most comprehensive comparison of the viewsheds was done between the SPOT DEM and USGS DEM. This comparison showed that of these DEMs, the USGS model performed slightly better than the SPOT model. This was measured in terms of the percentage of cells correctly classified. With the USGS model, the viewshed algorithm classified about 79% of the cells correctly, and with the SPOT model, about 72% of the cells were classified correctly.

According to the statistical tests performed using analysis of variance, the average percentage correctly classified by these two DEMs was not significantly different. The differences in the models were apparent only after an examination of the other possible avenues for measuring the ability of the DEMs to create accurate viewsheds. In

particular, this research compared the ability of the DEMs to determine all the area that was visible from a viewpoint or all that was not visible from a viewpoint. One question of interest was how much of the visible or not visible area was omitted from these viewshed calculations. A second question considered how much of the area determined to be visible (or not visible) had been incorrectly classified. These addressed the problem of errors of omission and commission.

The ramifications of the type of error in the viewshed may be explained in a simple example. Assume an area is partly visible and partly not visible from a given viewpoint. If the entire area were classified as not visible, then it is certain that all of the not visible area would be identified. The reliability of the cells classified as not visible would be low, since some of the cells should have been classified as visible. This would be like weeding a garden with a tractor plow. All the weeds would be gone, but the broccoli and tomatoes would be plowed under as well. It was only by looking at the viewsheds in this light that their differences became apparent.

The major finding of the research with regard to types of viewshed error was in the results that demonstrated the major factors contributing to the total percent of cells correctly identified. For the SPOT DEM, the total percentage correct was positively affected by the DEM's ability to identify not visible area and by the relative low number of visible cells that were included among the not visible ones. On the negative side, the visible area, as identified by the test DEM, included a fairly large number of not visible cells relatively to the number of visible ones. About 60 percent of the area identified as visible was actually not visible. For the USGS DEM, the total percentage correct was

positively affected by its ability to identify correctly much of the not visible area. This DEM suffered from "tractor plow in the garden" syndrome, however (described above). Seventy percent of the visible area was considered to be not visible by this DEM.

### The Development of Models of Error

Up to this point, this research provided background material for the development of the final models. The models of the path of error from DEMs to viewsheds developed in this research demonstrate the complexity of the problems of error propagation. The original plan for this research proposed the use of multiple regression to develop the model of error for the viewsheds. It was expected that the dependent variable, viewshed accuracy, would be a function of the set of independent variables outlined in Chapter VII. This type of regression model proved inadequate to incorporate the multi-dimensional nature of the problem. The concepts of path analysis proved a partial solution, but the quantitative manifestation of this method remains to be accomplished.

The models of error showed how landscape factors affected the error in the DEMs, which was then carried to the errors of omission or commission, and finally resulted in some effect on the accuracy of the viewsheds. The DEMs contributed to the problem of viewshed accuracy, but the landscape features played an equally important, but less direct, role. The height of the viewpoint was also an important factor in the viewshed accuracy. This variable is essentially random.

Since landscape features are variable, and each place on the earth wrought with its own peculiarities, generalization is difficult. Certainly, some respect must be given to

the unique attributes of a locality in understanding a model of that area. For analytical purposes, a DEM must adequately represent a particular place, and is not just an abstract depiction of some type of place similar to the place of interest. For this reason, proof of the validity of DEMs will remain elusive without field testing, at a fairly great expense.

### Recommendations for Future Research

Future research could carry further the models of error propagation. The methodology of structural equations could be used to test more extensively the relationships among the variables and to create a statistical model that defines the conceptual model. It may be, however, that other items could be added to the model prior to such testing.

An important item that could be added to the model is a better test for spatial autocorrelation. Work by Getis and Ord (1992) on local autocorrelation statistics could possibly be applied to these data. Much of the work in spatial autocorrelation, however, has been done with polygons, rather than with grid cells, making an exact application to the DEM question difficult without development of the proper algorithms.

In addition, a more complete test of viewsheds could be performed. It would be possible to test many more observation points with a program designed for that purpose. The computing power was not available for this project, but it is not an impossible goal.

Another addition would be to test a TIN model along with the grid DEMs. The TIN model would need to be transformed to grid for this comparison. The TIN-based

DEMs have become more common during the years of this research, and are an important part of the GIS DEM options currently available.

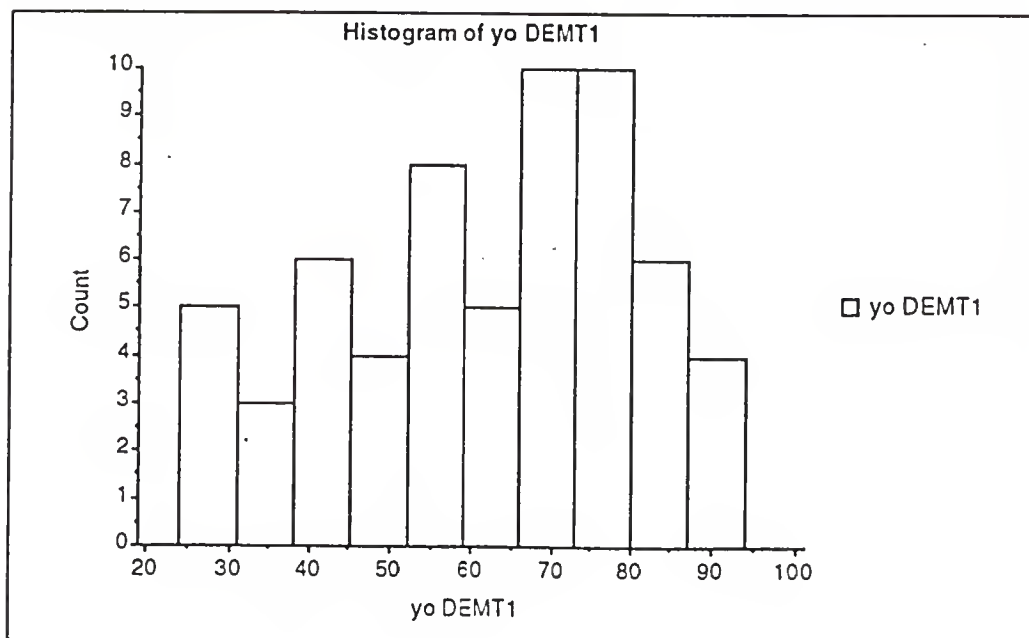
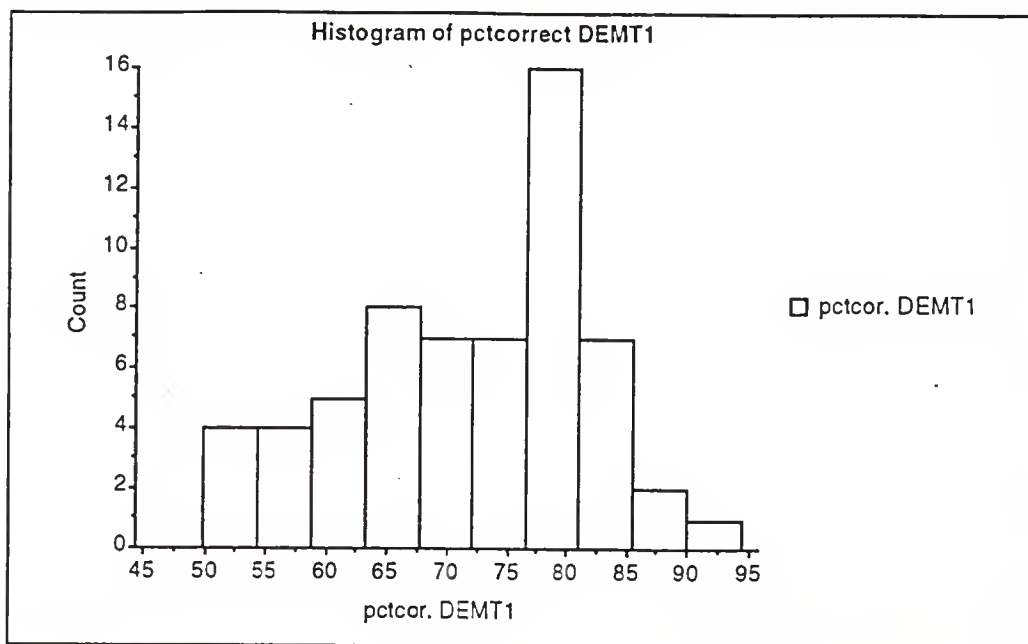
The manner in which the viewshed accuracy was assessed played an important role in these results. Fisher (1992) used the number of cells identified as visible as a measure of viewshed accuracy. The research carried out here strongly suggests that the same number of cells could be identified as visible but the viewsheds could still be quite different. The type of error, whether of commission or omission can make the viewshed estimates much different from each other. The percentage approach used here was affected by the fact that the amount of not visible area was always much greater than the amount of visible area. Some standardization of the percentages based on this factor would improve the measure used here.

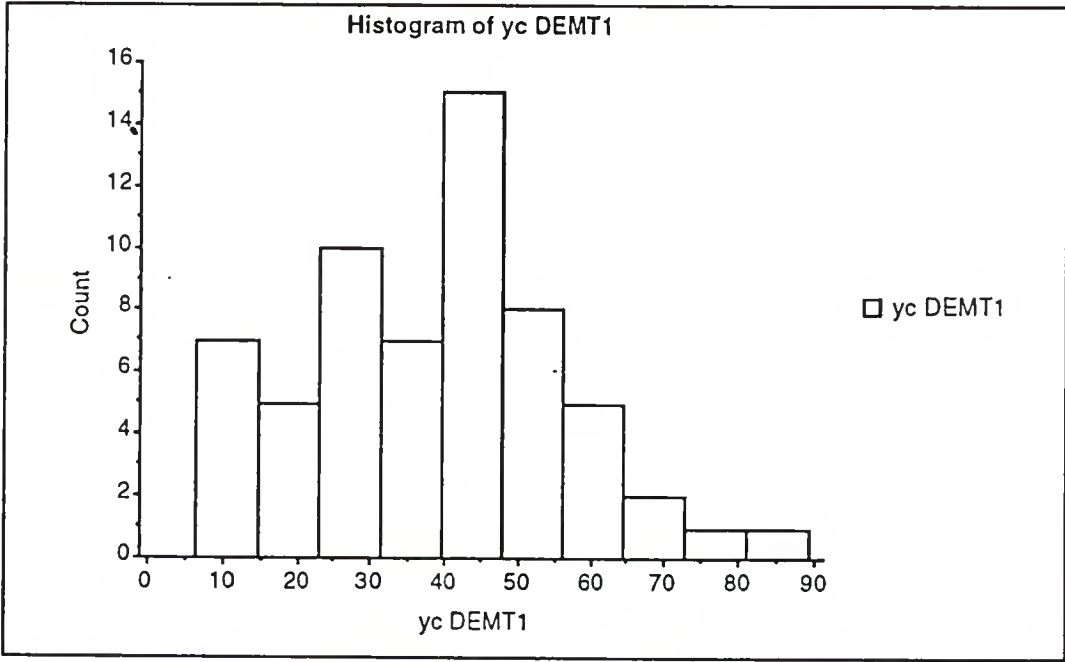
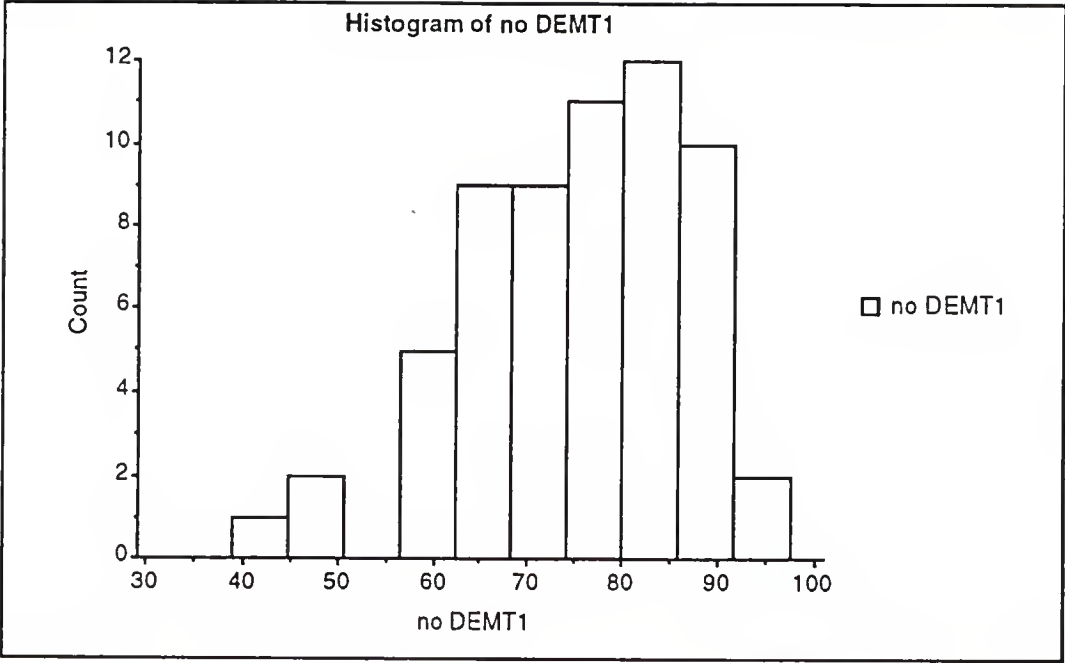
The viewshed algorithm, itself, was not discussed in depth in this paper. Any algorithm is prone to biases based on critical decisions made by the programmer. A comparison of algorithms with the same set of data may help to elucidate these biases. In addition, the validity of the both the algorithm and the accuracy of the DEMs could be assessed to some extent through field testing. This would add significantly to the value of this research.

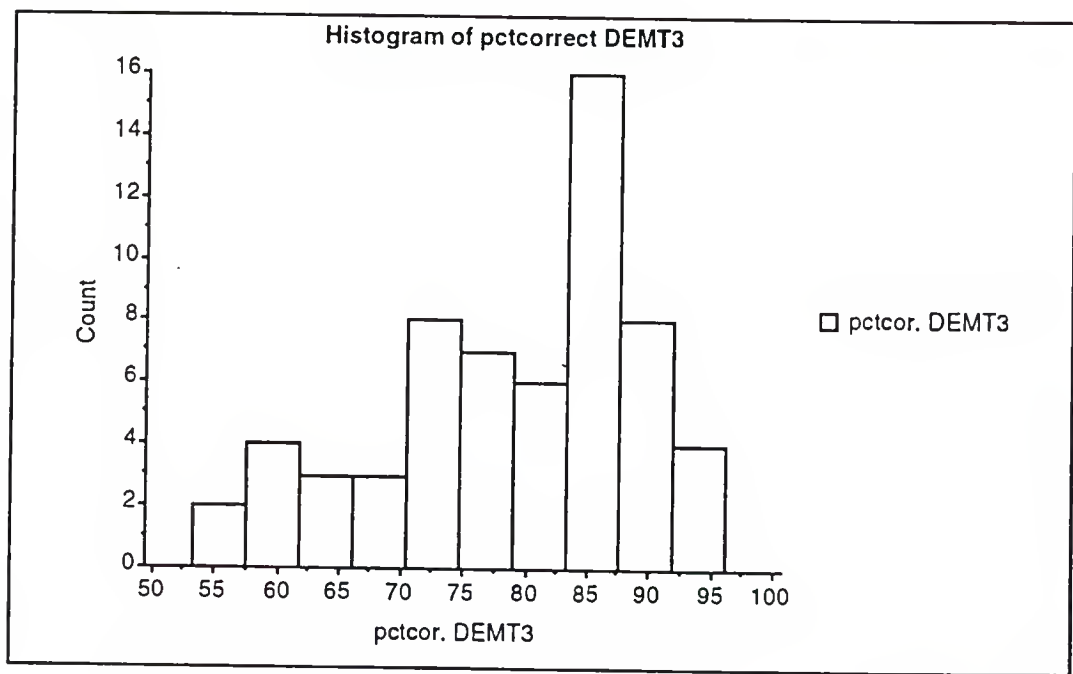
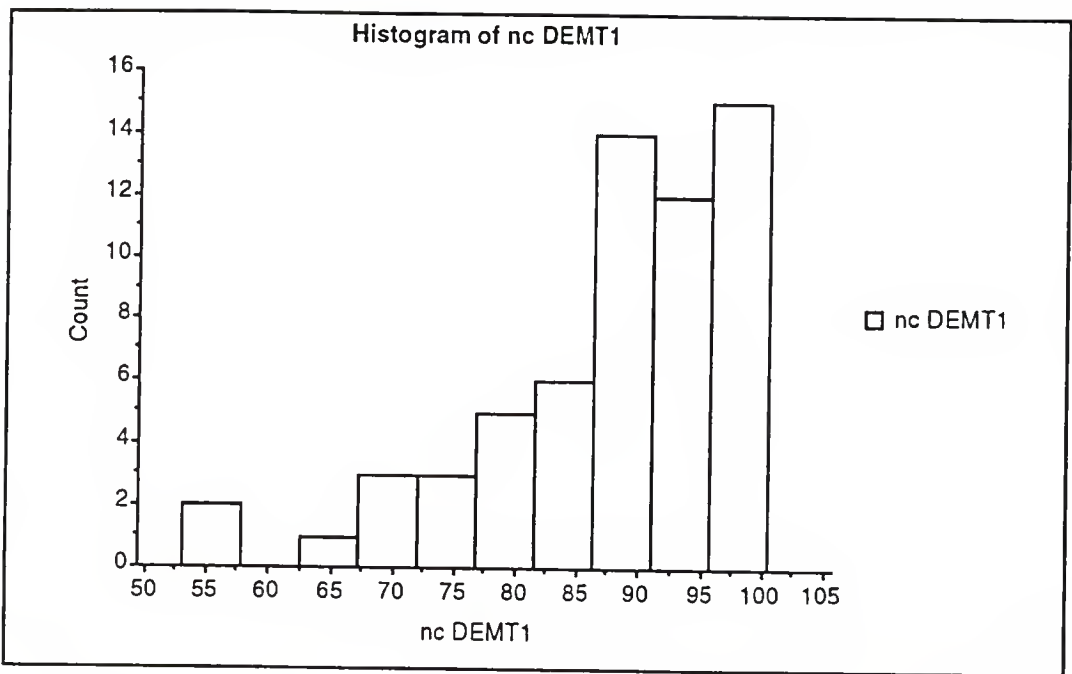
Overall, this work proved to be much more complex than was originally expected. The dataset gathered for this work was useful, but could be improved in several ways. Since the best method found for DEM creation was the contour interpolated model, the coverage of that model could be extended in order to provide a more rigorous test of its abilities over a variety of terrain. Other types of models, particularly those created from

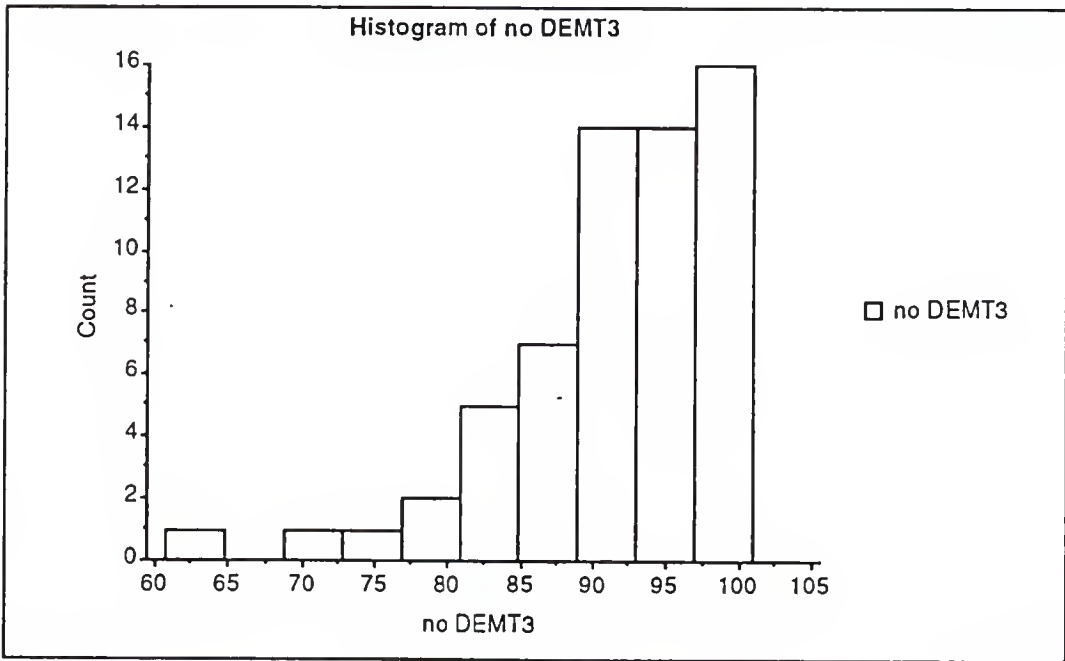
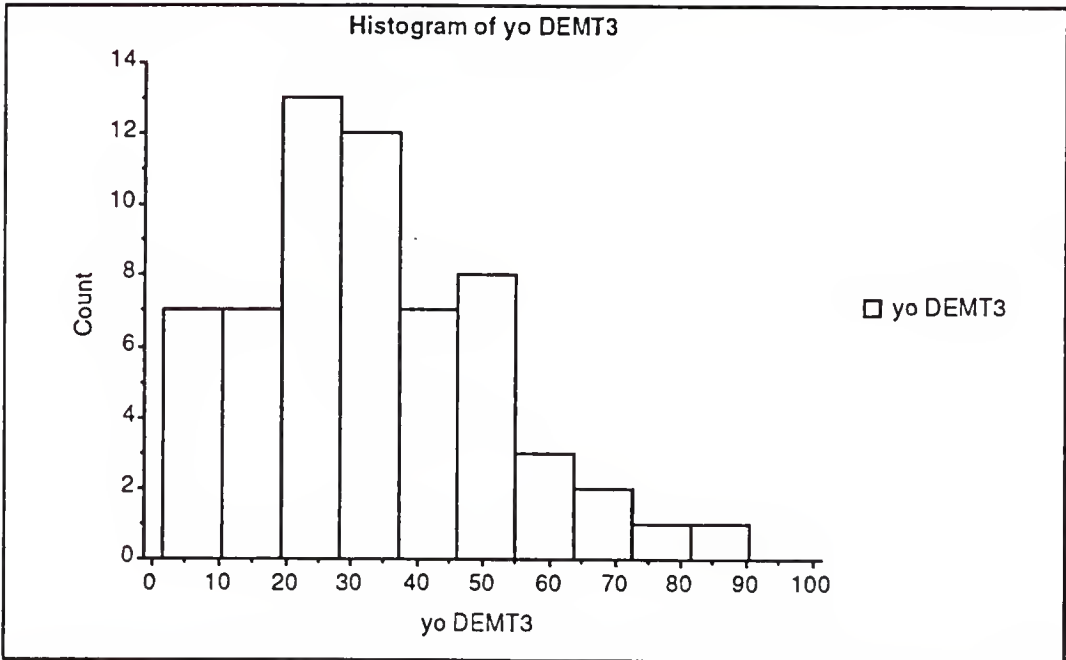
newer imaging systems, could also be included in the database and compared with the other models. The major value of this work was in determining the pattern of error in the DEMs created from the different methods, in revealing the great differences in viewshed estimations made by supposedly similar DEMs, and in introducing path analysis as an appropriate methodology in developing a better understanding of error propagation from digital data to a geographic information system analysis.

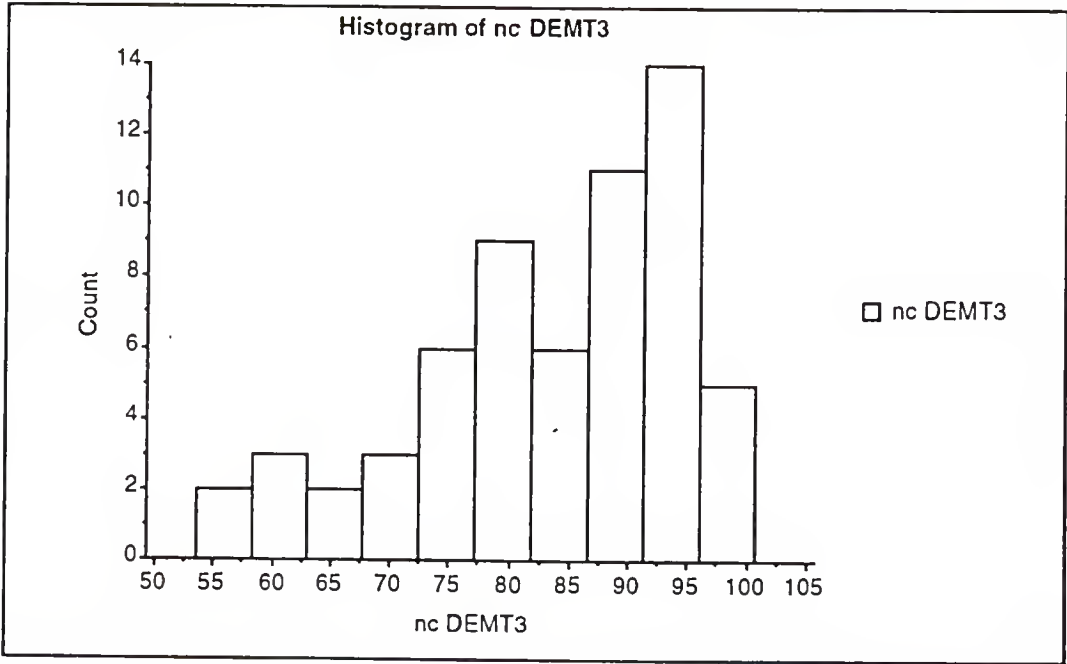
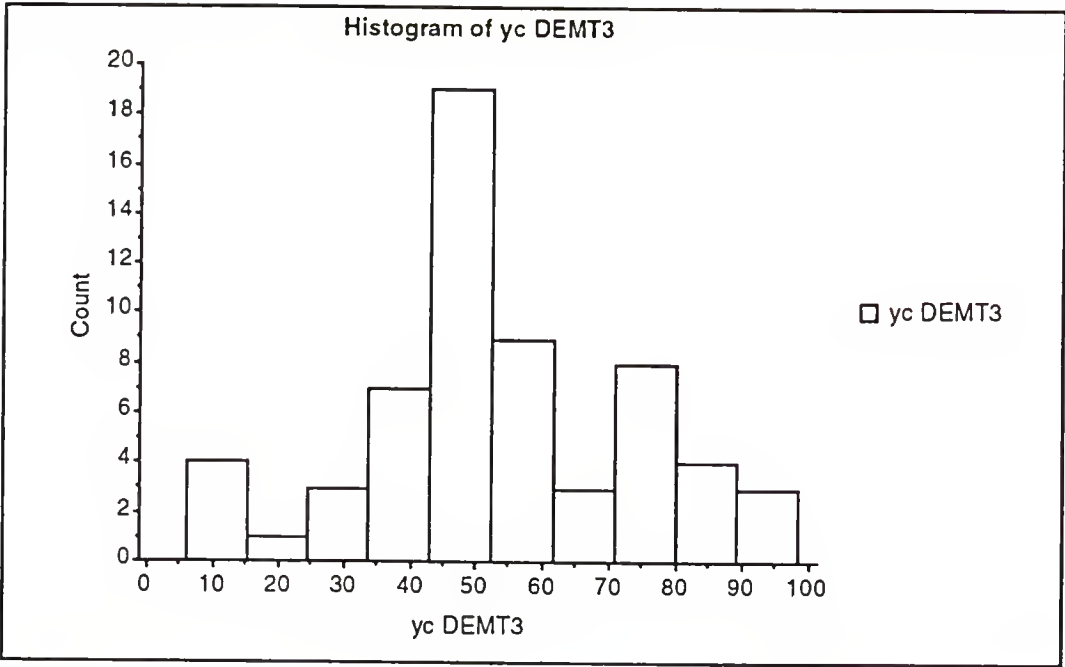
APPENDIX  
HISTOGRAMS OF VARIABLES USED IN THE ERROR MODELS

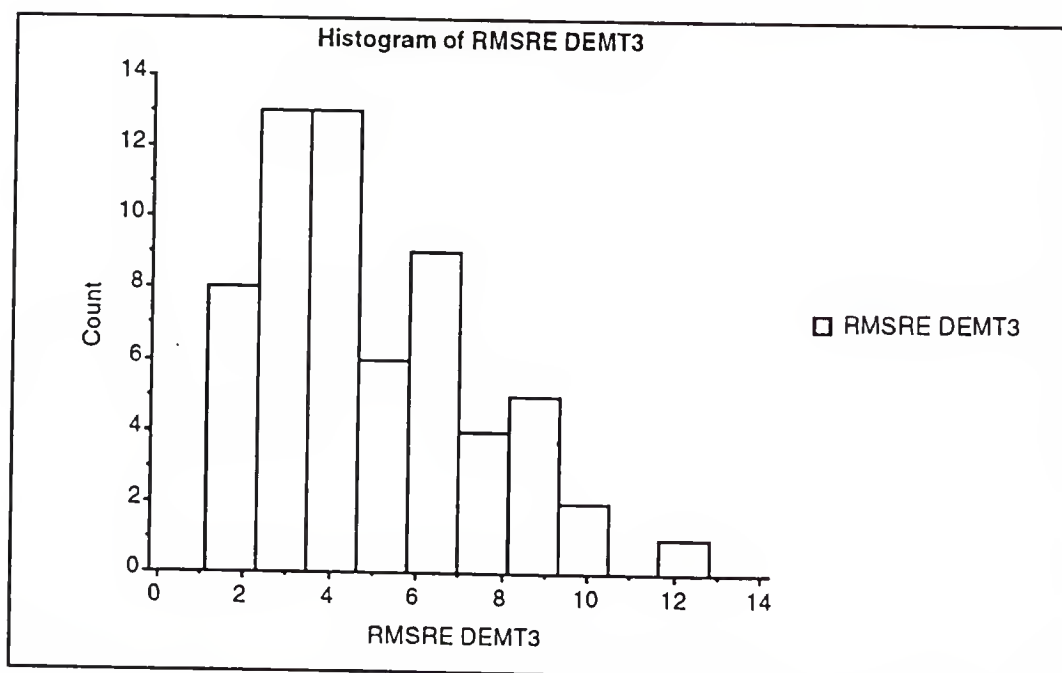
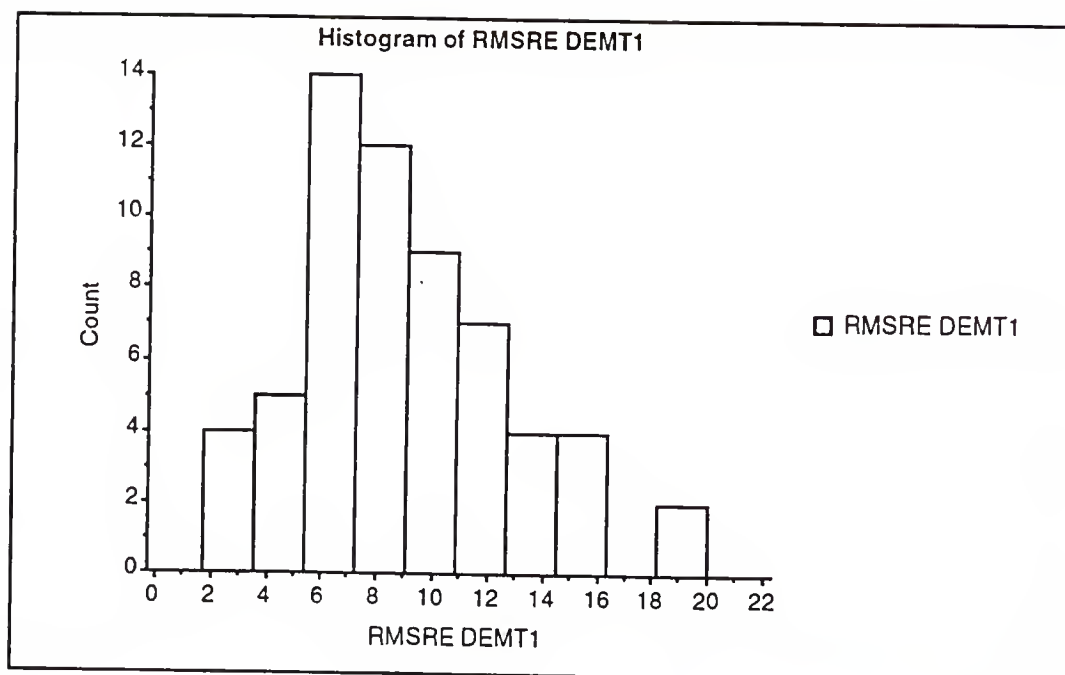


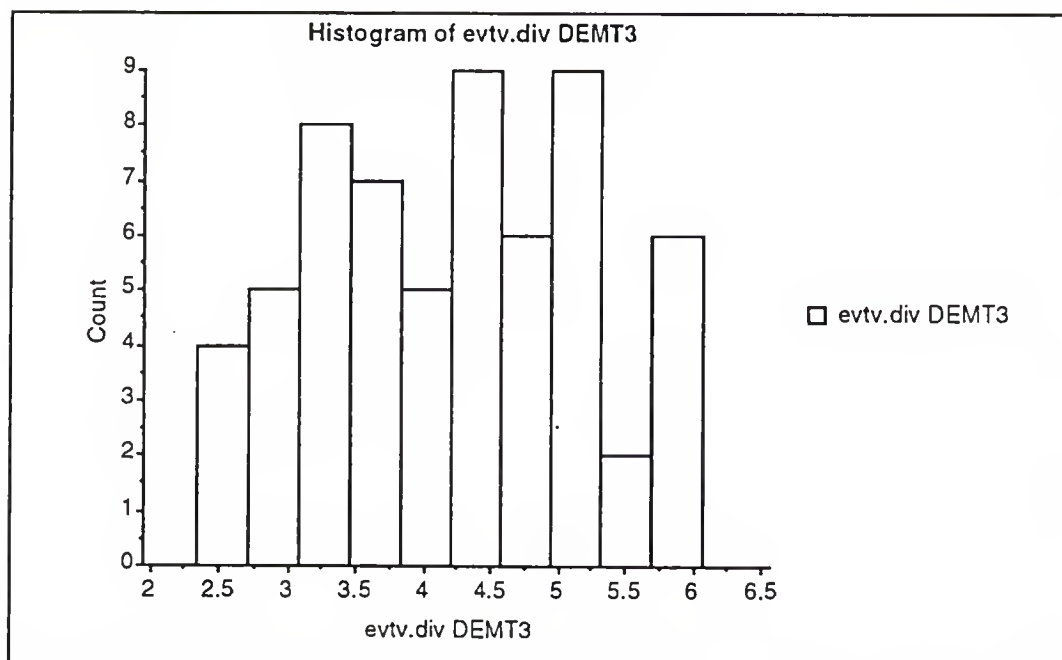
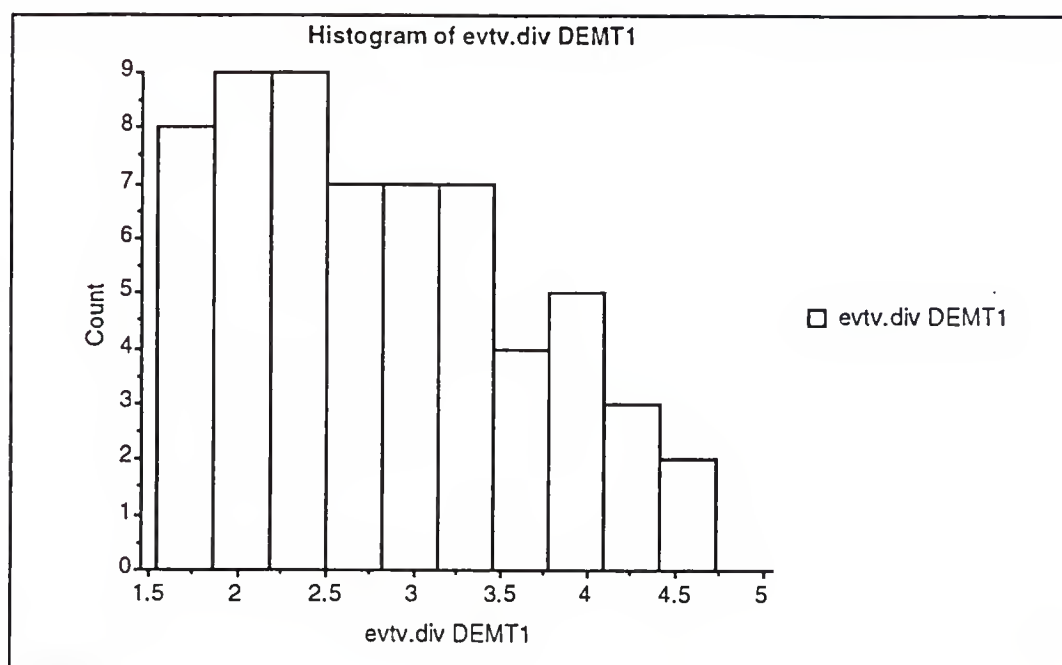


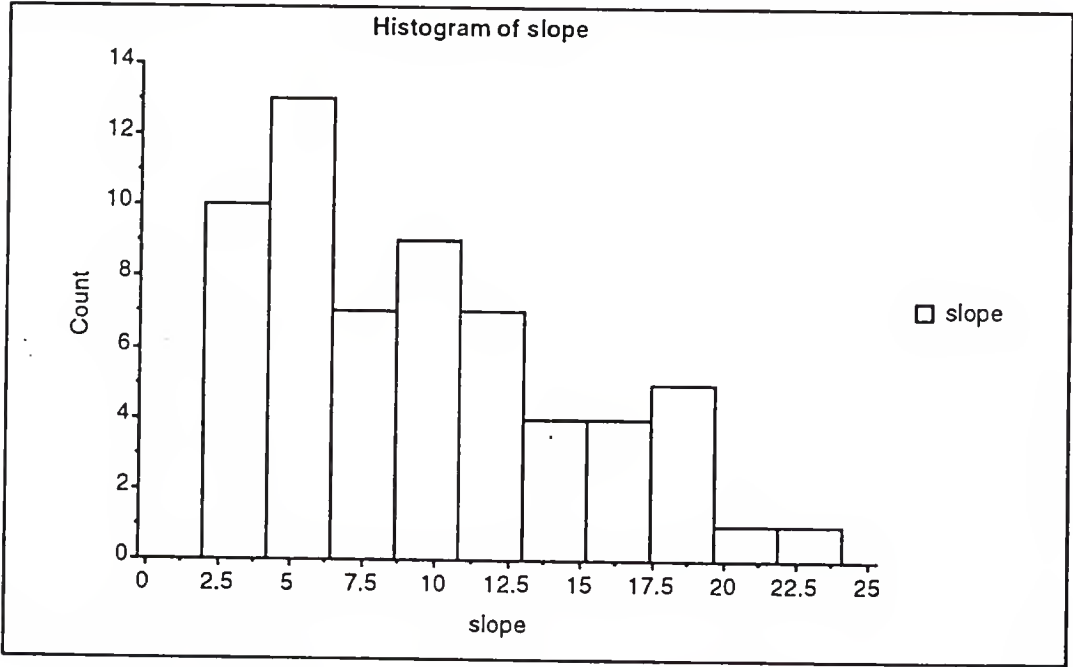
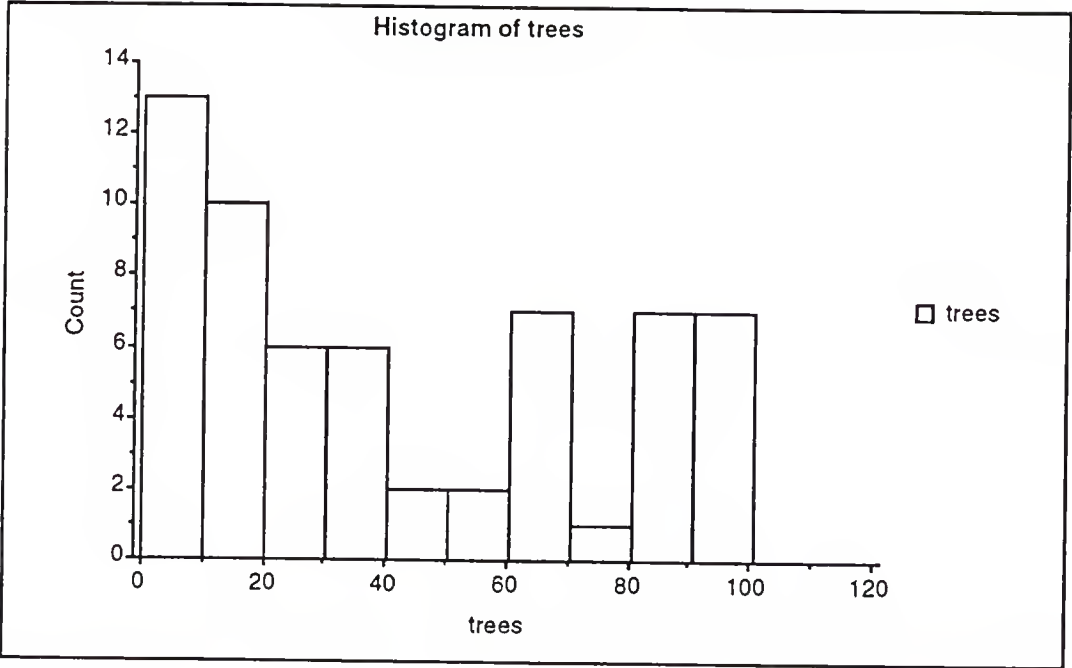


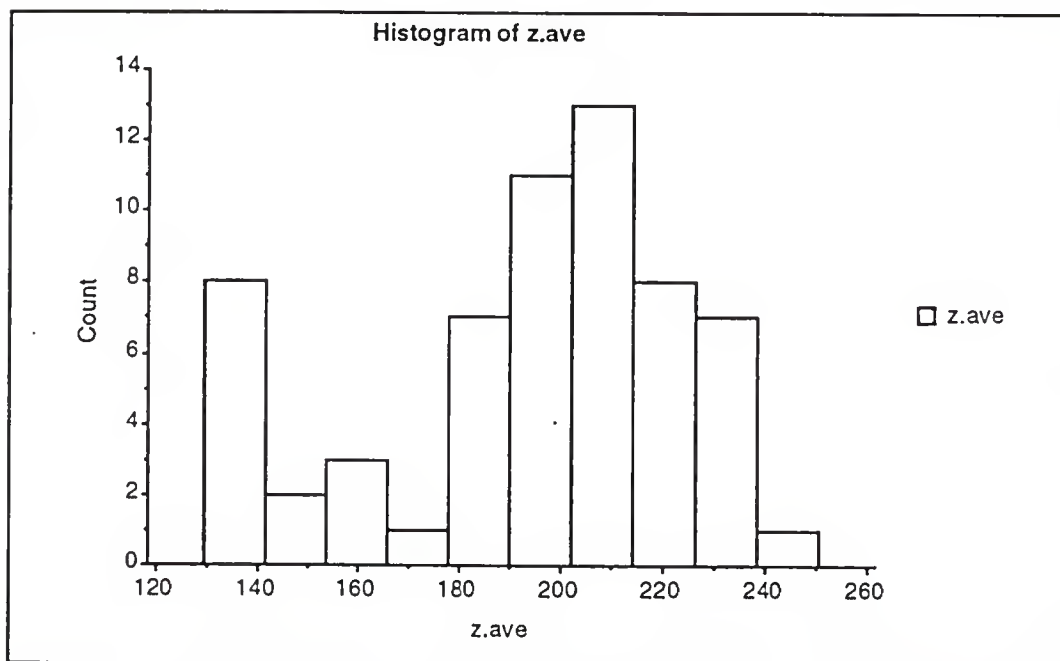
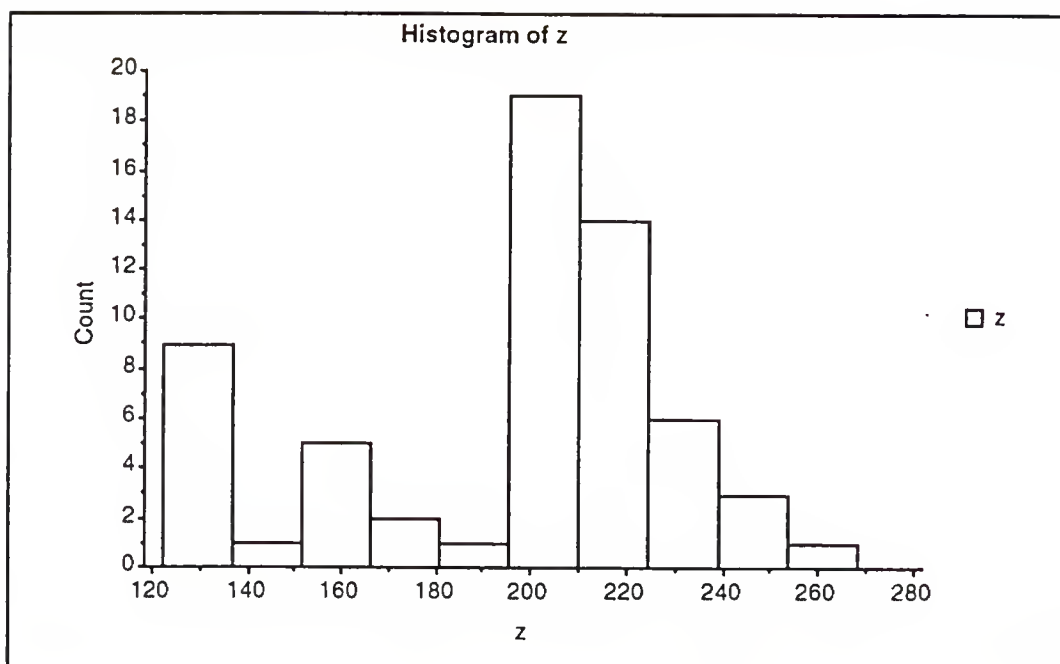












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## BIOGRAPHICAL SKETCH

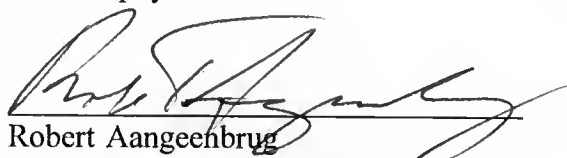
Marilyn O'Hara Ruiz was born in Nauvoo, Illinois, in 1959. She is the fifth child of the eight children of Jim and Ruth O'Hara. At the age of nine, after living in various small towns in northern Illinois, she moved with her family to Champaign, Illinois. There, she finished high school in 1977, and then enrolled in Parkland Community College. After considering various academic majors, including music, French, and urban planning, Marilyn decided to study geography. She graduated from the University of Illinois in 1982. The following year, she entered the graduate program in geography at the University of Illinois. There, she studied cartography with Jim Bier and social geography with Curt Roseman and Marilyn Brown.

After completing a master's degree in geography in 1985, Marilyn spent one year as a self-employed cartographer. She met and married Ivan Ruiz during that time. In 1987, Marilyn started work for the U.S. Army Construction Engineering Research Laboratory in Champaign, Illinois. There, she worked as a cartographer with a group that had developed the GRASS geographic information system (GIS). She left her work there to pursue a Ph.D. at the University of Florida, in Gainesville. Marilyn's current research grew out of her experience at the USACERL. Marilyn is also interested in health-related applications of GIS and plans to continue work in that area at her current position as Assistant Professor of Geography at the Florida State University in Tallahassee, Florida.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

  
Grant Ian Thrall, Chair  
Professor of Geography

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Robert Aangeenbrug  
Professor of Geography  
University of South Florida

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Bon A. DeWitt  
Assistant Professor of Civil Engineering

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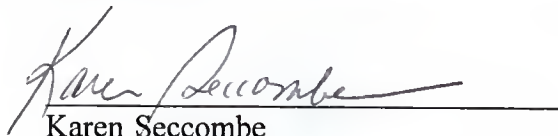
  
John Dunkle  
Professor of Geography

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Timothy Fik  
Associate Professor of Geography

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Karen Seccombe  
Associate Professor of Sociology

This dissertation was submitted to the Graduate Faculty of the Department of Geography in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

May, 1995

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Dean, Graduate School

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